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PROJECT ADMINISTRATION DATA SHEET

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e: Electrical Evaluation of a Brink's Safe Case Design

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(or) Company/Industrial Proprietary: ______

STRICTIONS

Attached N/A Supplemental Information Sheet for Additional Requirements.

vel: Foreign travel must have prior approval – Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

ipment: Title vests with Sponsor; however, none proposed.

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earch Administrative Network	Research Security Services	Research Communications (2)
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curement/EES Supply Services	Library	Other Scott Crowgey

ORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 12/7/83

ect No. A-3452 ~~School~~/Lab ECSL

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ect Director(s) Steve Sharpe/Scott Crowgey GTRI / ~~GIT~~

isor Brinks Engineering Company

Electrical Evaluation of a Brink's Safe Case Design

ctive Completion Date: 6/18/83 (Performance) 6/18/83 (Reports)

t/Contract Closeout Actions Remaining:

- [ ] None
- [x] Final Invoice or Final Fiscal Report
- [ ] Closing Documents
- [ ] Final Report of Inventions
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
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FINAL REPORT

PROJECT A-3452

ELECTRICAL SAFETY EVALUATION OF A BRINK'S SAFE CASE DESIGN

By

S. R. Crowgey and S. M. Sharpe

October 1983

Prepared for

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Prepared by

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FOREWORD

The research on this six-month program was carried out by personnel of the Biomedical Research Division of the Electronics and Computer Systems Laboratory at the Georgia Institute of Technology, Atlanta, Georgia 30332. Dr. Steve Sharpe and Dr. Scott Crowgey served as Principal Investigators. The program, which was sponsored by the Brink's Engineering Company, was designated by Georgia Tech as Project A-3452.

This Final Report covers work which was performed from 4 January 1983 through 18 June 1983. This work was made possible through the combined efforts of many people at Brink's Engineering Company and at the Georgia Institute of Technology. The authors would especially like to thank Mr. Bill Gunn and Mr. Bill Heath at Brink's Engineering Company, both of whom contributed significantly to this program's success.

Respectfully submitted,

Scott R. Crowgey, M.D.
Principal Investigator

APPROVED

J. C. Toler, Chief
Biomedical Research Division

SUMMARY

The objectives of this investigation were to: (1) analyze the circuit of the Brink's Safe Case Design and measure electrical parameters under conditions simulating human contact and (2) prepare a formal report presenting measurement results compared to safe limits for electrical shock as published in the open literature.

Analysis of the circuit design was performed by Dr. Steve Sharpe who has previously relayed his analysis to the Brink's Engineering Company by means of an ongoing interaction with Mr. Bill Gunn and Mr. Bill Heath. As a result of this interaction and of preliminary results of an extensive literature review, the original Safe Case Design went through two major changes prior to arriving at the final design. Measurements and analysis of data for each of the three Safe Case Designs were conducted requiring extension of a three-month program to a six-month program. Results for each of the three Safe Case designs will be presented in this report and analyzed with respect to established safety thresholds in the open literature.

A review of the literature revealed that current is the parameter which best defines the safety threshold for any type of electrical contact. Safe Case Designs #1 and #2 both showed a wide variation in current amplitudes over the resistance range commonly used to simulate the human body. Currents varied from being at or above safety thresholds for low resistances to being ineffective for stimulation at high resistances. Safe Case Design #3, however, provided a fairly constant current amplitude over the whole range of resistances tested and was consistently below the fibrillation thresholds of danger. Therefore, Safe Case Design #3 was felt to be relatively safe for the purpose of providing a noxious electric stimulus.

Burn potentials were assessed for each Safe Case design. Designs #1 and #2 were both characterized by low energy outputs and low probabilities of causing surface burns. Design #3 was characterized by higher energy outputs over time which had the potential for causing skin surface burns if contact is prolonged.

Finally, it must be emphasized that this analysis of safety is based on reported fibrillation and "let-go" thresholds for the average healthy

adult male. The Safe Case should not be carried by persons with heart pacemakers or by persons with known heart disease. For this population, even small and innocent electrical shocks may result in ventricular fibrillation and death. C. F. Dalziel states [6]:

> "Due to variations in the physical condition existing among men it must be stressed that no electric shock can be considered as absolutely safe, however establishing a current below which ventricular fibrillation is unlikely should be of practical value in improving the safety of electrical installations."

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

The research described in this Final Report was the result of efforts performed during a six-month period to evaluate the electric safety of the Brink's Safe Case. Efforts involved during this period included an extensive review of the open literature regarding safe limits for electrical shock, measurements of the electric parameters of the Safe Case under conditions simulating human contact, and analysis of the measurements and comparison of these results with known safe limits fór electrical shock as published in the open literature.

The first section of this report will summarize results of the literature survey, initially describing the known hazards of human contact with electrical shock followed by reported thresholds of danger along with brief discussions of the hazards of impulse currents and the hazards of electrical burns. The second section describes results from the evaluations of three Safe Case Designs along with comparisons of the electrical parameters with reported thresholds of safety.

LITERATURE REVIEW

Electrical Injuries

Electrical injuries can result from a variety of mechanisms. Dr. Butler and Dr. Gant in 1977 [3] listed the following as possible mechanisms:

"1. direct contact with an energized object...;
2. arcing of electricity to a grounded victim;
3. exposure to the intense heat of an "arc" flash;
4. exposure to flames from ignited clothing and environment; and
5. falls precipitated by an electrical accident."

The effect of the electrical current in electrical injuries depends primarily on the parameters of current, voltage, and resistance at the time of electrical contact. Additional factors which must also be considered in any type of biological electrical contact include the following [2,9,31]:

1. current pathway through the body,
2. physical condition of the victim,
3. frequency of the current,
4. magnitude of the current,
5. shock duration,
6. waveform of the current, and
7. the phase of the heart cycle at the instant of the shock.

As can be inferred from the above list, it is the current which determines the amount of danger from an electrical contact. Variables which further affect the degree of danger include the frequency, magnitude, duration, and waveform of the current produced. Current flow can cause tissue damage by the generation of heat resulting in burns and coagulation necrosis; however, these thermal injuries are in general not life-threatening unless extensive. Current flow through the body can also cause a stimulation effect on the nerves and muscles in the tissues it passes through, and, depending on the tissue, can result in lethal effects.

Current flow which is limited to an extremity may produce painful muscle contractions, and, if the frequency is high enough, may result in tetanic contractions (maximal continuous contraction of the muscles not subject to voluntary control). This type of reaction usually causes no lasting damage other than the memory of a very disagreeable experience. However, should the current be of a large enough magnitude, the intense muscular contractions produced may sometimes result in fractures of the associated bones. Currents flowing through the lower nerve centers and spinal column may result in ejaculation at low intensities and in permanent neurological damage if the intensity is enough to produce thermal injuries. Currents passed through the head may result in unconsciousness and convulsions. Current flow through the nerve centers controlling respiration may produce respiratory inhibition which is usually only temporary, lasting only a few minutes to as long as a few hours after interruption of the current flow. Alternating currents flowing across the chest may result in tetanic contractions of the chest muscles, thus inhibiting respiration during the duration of current flow [2,4,9,26,30]. The most lethal form of current flow through the body is that which involves the heart muscle, resulting in a condition known as ventricular fibrillation. Ventricular fibrillation is an uncoordinated asynchronous contraction of the ventricular muscle fibers as opposed to the normal coordinated rhythmic contractions which provide a good cardiac output of blood to the body [1,2,4]. During this condition, the heart quivers instead of beating and cannot effectively pump blood through the body. Once ventricular fibrillation starts, the blood circulation ceases, resulting in unconsciousness within 10 seconds and subsequent irreversible brain damage and possible death in 4 to 6 minutes unless cardiopulmonary resuscitation is begun [1,2]. This condition is only rarely spontaneously reversible, is usually fatal, and is generally the cause of death in instantaneous electrocutions.

Body Resistance

Most electrical injuries occur as a result of the contact of a body with a known potential difference. Again, it must be emphasized that it is the current produced by this contact and <u>not</u> the voltage which determines the amount of injury incurred by this contact. Therefore, as a result of Ohm's Law, the body impedance is quite often a major factor in the determination of the severity of an electrical shock [2,4,14,23]. Ohm's Law states that $I = E/R$, or current (I) is defined by the potential difference (E) divided by the resistance of the body (R) across the potential difference. The resistances of various body tissues vary widely, being greatest in bone and diminishing in the following order: bone, fat, tendon, skin, muscle, vessel, and nerve. Body impedances also vary with frequency. For low frequencies the body impedance is essentially resistive. Above 1000 Hz the body impedance begins to exhibit nonlinear characteristics due to its cellular make-up [4,7]; however, man's decreasing sensitivity with increasing frequency suggests there is less and less stimulation effect as the frequency increases [7]. As the stimulation effect decreases, the potential for thermal injury increases. Skin resistance is the most important component of the body impedance since current must first pass through the skin before it can reach the underlying lower resistance tissues. Average skin resistance is 40,000 ohms, but resistance of the calloused palm may be as high as 1,000,000 ohms while that of moist clean skin may be as low as 300 ohms [2,4,18,31]. It must also be remembered that skin with its initially high resistance will gradually lose its protective capability with prolonged electrical contact due to vasodilation at first followed by breakdown of the skin secondary to blisters and burns. In developing a model for the prediction of electrical shock hazards, Charles Dalziel [4,8,18] recommended a minimum value of 500 ohms. He states:

> "A value of 500 ohms is commonly used as the minimum resistance of the human body between major extremities and this value is commonly used in estimating shock currents during industrial accidents. A value of 1500 ohms, which may be too high, is used to represent the body circuit between the normal perspiring hands of a worker and in estimating currents of the reaction current level." [4]

The value of 500 ohms is used to represent the internal body resistance excluding the skin. It should be noted that the Bell System and other industries frequently use the value of 1500 ohms in estimating shock hazards [2].

Thresholds of Hazard

As a result of extensive research by many different investigators, it has been shown that the current flowing between two conductors of different potentials produces first sensation followed by muscle contraction, ventricular fibrillation, defibrillation, and finally burns. This is the order of events seen as current intensity is increased. It has also been well documented that the amount of current required for physiologic effects is proportional to the frequency of the alternating current and that direct current is tolerated at much higher thresholds than alternating current. In determining the safety of various current waveforms, the literature contains good documentation only for sinusoidal currents of varying frequency. Very little information is available on currents at frequencies other than power line frequencies, and even less data is available for currents with a waveform that is not sinusoidal. Charles Dalziel [4-11] has collected probably the largest volume of data on current thresholds of safety. He has divided current thresholds into three categories: Perception Thresholds, Let-Go Thresholds, and Fibrillation Thresholds.

Perception Thresholds

The Perception Threshold is defined as the current at which the presence of current can be sensed [1,2,4,7,18,26,31]. Stimulation with direct current produces a sensation of warmth while stimulation with alternating current produces a tingling sensation. For direct current the mean threshold of sensation for men was 5.2 milliamperes (mA) and for women was 3.5 mA for electrical contact with the hand. In contrast, for alternating current at 60 Hertz the mean threshold was 1.1 mA (rms) for men and 0.7 mA (rms) for women [2,7]. Although currents of this level pose little biological danger, they are important in the setting of limits for household electrical devices, since these currents could possibly produce a startle reaction in a person resulting in a fall or some other involuntary reaction which could be hazardous to the individual.

Pain thresholds show a great degree of variation between individuals and with skin impedance and current duration [2,9,29]. In general, pain thresholds for electrical current are lowered with increases in pulse duration and in the number of pulses applied [2,29]. Pain also seems to be closely related to current density.

Let-Go Thresholds

As current flowing in an extremity increases, the sensations of warmth and tingling also increase in severity until muscular reactions and pain develop. These muscular reactions are especially marked at alternating current frequencies between 10 hertz and 200 hertz. Eventually, a current level is reached at which muscular stimulation and the resultant muscular contractions are so severe that the person cannot voluntarily release an electrical contact. The person is then said to "freeze" to the contact [1,2,4,10,11,18,26,31]. The maximum current that a person can tolerate and still release the conductor using the muscles directly stimulated is called the "let-go" threshold [2,4,9,10,11]. Dalziel has determined both the Perception and the Let-Go current thresholds for sinusoidal currents over a wide range of frequencies and for a large population of healthy males and females [2,4,7,10,11]. It has also been well documented than an individual can tolerate prolonged and repeated exposure to his "Let-Go" current with no serious after effects other than residual muscle aches from the contractions [2,4,11].

Dalziel has analyzed his data in terms of population percentiles for both Perception and Let-Go Thresholds. A graph of these percentile thresholds for varying frequencies has been plotted in Figure 1 and is an adaptation of Dalziel's own data [7,11]. The three lines for each group represent, from top to bottom, the 1/2 percentile, the 50 percentile, and the 99.5 percentile. An interpretation of the meaning of these percentile thresholds follows: for the Let-Go current levels, the 99.5 percentile threshold is that current at which 99.5 percent of a large group of healthy adults could release themselves from contact with a current [2,4,10,11]. For the Perception Levels, the 99.5 percentile current threshold is that current at which 99.5 percent of a large group of healthy adults could just perceive the presence of a current. In the past, the 99.5 percentile Let-Go Threshold has served as a definition of a reasonably safe electric current. However, as already mentioned a person can tolerate prolonged and repeated exposure to his Let-Go current without serious harm.

For most normal healthy adult men the 99.5 percentile Let-Go Threshold at 60 hertz is 9 mA (rms) while for normal adult women this level is 6mA (rms). Although Figure 1 displays the threshold levels for increasing frequency, there is very little information available for lower frequencies. As the current frequency decreases below 10 hertz, the Let-Go Threshold increases. Table 1 lists the Let-Go current levels for lower frequencies and for the different percentile groups as approximated from Dalziel's graph [11] of sine wave Let-Go Thresholds versus frequency.

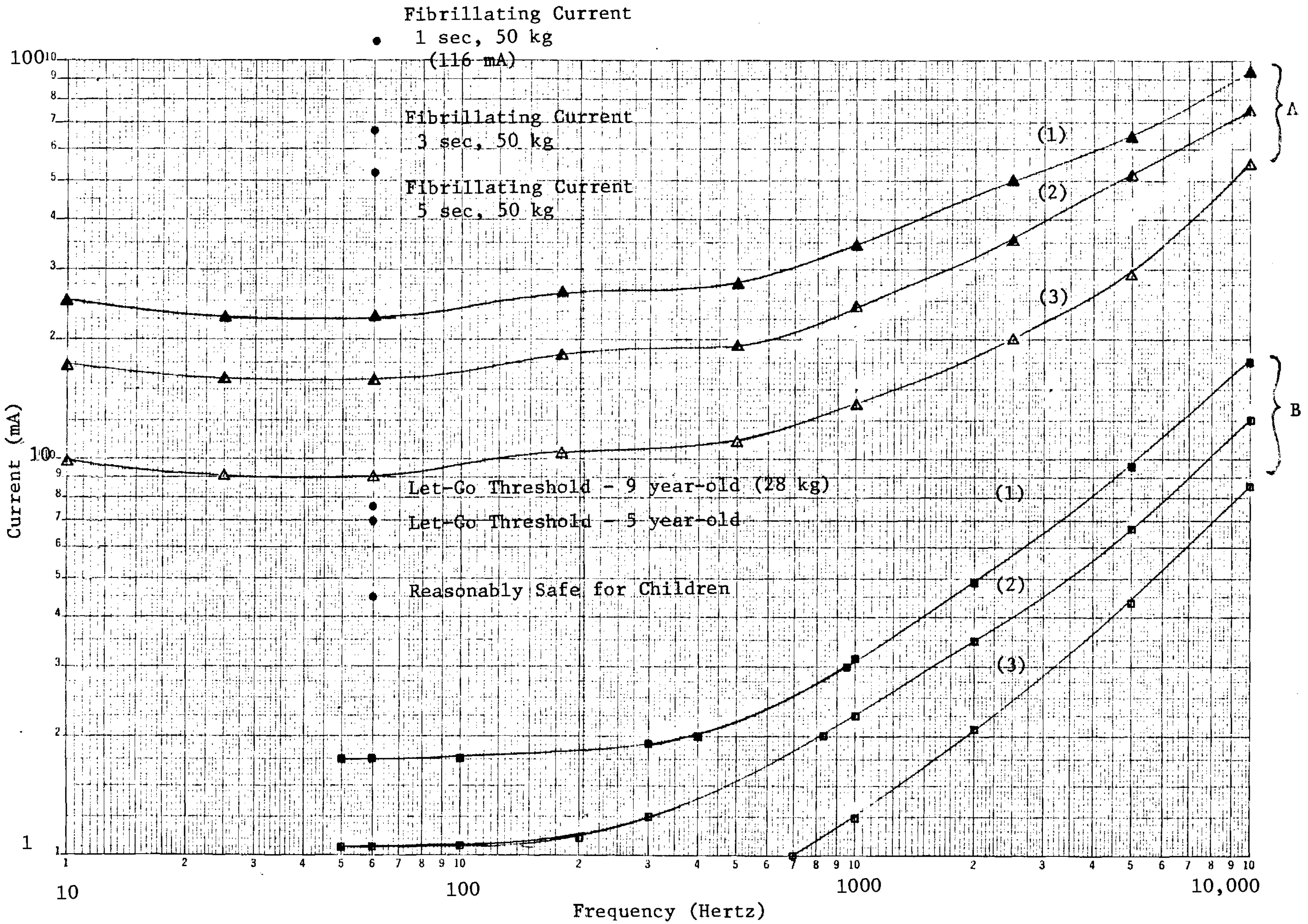

Figure 1. Perception (A) and Let-Go (B) Percentile Thresholds vs. Frequency Plotted from Data Obtained by Charles Dalziel (7,11). Each Group of Thresholds Consist of Three Lines Representing (1) 0.5 Percentile, (2) 50 Percentile, and (3) 99.5 Percentile. Literature Values for Minimum Fibrillating Currents and Known Let-Go Thresholds for Children are Shown.

TABLE 1

SINE-WAVE LET-GO THRESHOLDS FOR MEN (AND WOMEN IN PARENTHESES) AS A FUNCTION OF LOW FREQUENCIES

(Derived from graph by Dalziel [11])

Frequency	99.5%	Mean	0.5%
60 Hz	9 mA rms (6)	15.87 mA rms (10.5)	22.7 mA rms (15)
10 Hz	10 mA rms	16.3 mA rms	25 mA rms
5 Hz	14 mA rms	23.4 mA rms	37 mA rms
D.C. (Release Current)	62 mA (41)	73.7 mA	87 mA

The data on direct current (dc) Let-Go Thresholds also included in Table 1 requires further explanation. Obviously, for direct current there will be no repetitive or tetanic contractions of the muscle as there is with alternating current. However, on steadily increasing the direct currents being applied to the hand, the sensations of internal heating will increase and sudden changes in current magnitudes will produce muscular contractions while interruption of the current will produce a severe, objectionable shock. In Dalziel's experiments [11], the maximum dc current level a subject would tolerate and still release the contact voluntarily was termed the release current and was equated with alternating current Let-Go Thresholds. Thus, this level represents a voluntary endurance limit above which a certain percentage would refuse to tolerate any more punishment as opposed to the Let-Go Threshold which is an involuntary limit.

Prior to discussing Fibrillation Thresholds, mention should be made of the effects of currents above Let-Go but less than Fibrillation levels. Dalziel and Lee [2,4,5] both found that 60 Hertz currents in this range, typically between 18 to 22 mA (rms) or more, flowing across the chest cavity would result in inhibition of respiration and signs of impending asphyxia until the current contact was broken. On interruption of the current, normal respirations would resume.

Fibrillation Thresholds

The intensity of current resulting in ventricular fibrillation is the ultimate determination of the threshold of safety, since electrical contact at or above the Fibrillation Threshold will result in death without medical intervention. Although the Perception Thresholds and Let-Go Thresholds are commonly used in the evaluation of electrical appliances for consumer protection, this report is primarily concerned with evaluating the safety of a device, the purpose of which is to shock a potential criminal. For this purpose the Ventricular Fibrillation Thresholds will be used to determine the safety of the device.

In determining Fibrillation Thresholds, the literature has customarily been as conservative as possible by evaluating the thresholds assuming the worst possible conditions. It has been found that the worst possible current pathway through the body is a pathway parallel to the body axis, as from the forearm to the opposite leg [2,9,13,21,26]. In dog experiments, W. B. Kouwenhoven, et al. [21] found that 9-10% of the total current passing through the body in this orientation would pass through the heart. In contrast, for a pathway transverse to the body axis, only 3% of the total current would pass through the heart. Thus, current pathways transverse to the body axis, as from one forearm to the opposite forearm, are not as dangerous as longitudinal pathways. Also, current pathways across the chest, from chest to forearm, from head to leg, and from forearm to opposite leg all exhibit almost identical fibrillation thresholds [13]. Thus, most fibrillation thresholds have been established for a pathway from one arm to the opposite leg.

Fibrillation Thresholds are also commonly interpreted with knowledge of the fact that the susceptibility of the heart to fibrillation is greatest during the partial refractory phase of the cardiac cycle which constitutes about 20 percent of the whole cardiac cycle and which occurs simultaneously with the T wave of the EKG [2,9,13,27]. With shocks of about 0.1 second duration or less, it is practically impossible to produce ventricular fibrillation unless the shocks coincide at least in part with this sensitive phase of the cardiac cycle. Fibrillation Thresholds for short shock durations are commonly derived from tests in which the shock corresponds with this phase of the cardiac cycle, thus assuming worst case conditions. Therefore, all fibrillation thresholds are interpreted as the level of current which would cause fibrillation when applied during the most sensitive phase of the cardiac cycle.

No data is available relating the effects of age and health on fibrillation thresholds, and it must be remembered that all current thresholds are recommended only for healthy men and women, usually between the ages of 20 and 46. Although the threshold levels are commonly calculated assuming a conservative weight of 50 kilograms (110 pounds), the applicability of these levels to the elderly with possible heart conditions must be an item of concern. In addition, it has been shown that a 60 Hz current as low as 180 microamperes through a myocardial electrode can produce ventricular fibrillation in humans [26], and it has been estimated that currents as low as 20 microamperes through an intracardiac electrode could also produce fibrillation. Thus, the person with a cardiac pacemaker must always be considered an extreme risk for any type of electrical shock, and the fibrillation thresholds in the literature will not apply to this population.

Practically all available information on fibrillating currents has been obtained as a result of animal experimentation, from which the data has been extrapolated to apply to the human case. All investigators appear to agree that there is a current-weight relationship between various species, as well as a relationship to the duration of stimulation [2,4-6, 9, 13, 26]. Dalziel has summarized this data in an electrocution equation for men which states that the minimum 60 Hz electric current causing ventricular fibrillation is proportional to body weight and inversely proportional to the square root of shock duration, or $I=K/\sqrt{T}$. In this expression, I is the critical current in milliamperes rms of the 60 Hz sinusoidal current, K is a constant determined on the basis of body weight, and T is the duration of the shock in seconds. Dalziel and Lee suggest the conservative estimate for the body weight of man as 50 kg (110 lb) which would make the constant K=116 for the minimum fibrillating current and K=185 for the definite fibrillating current [2,4,5,26]. A value for K of 100 has been recommended for children [1]. The minimum fibrillating current is defined as the current at which only one-half percent of the population would be in danger of fibrillation while the definite fibrillating current is that current at which 99.5 percent of the population would be in danger of ventricular fibrillation [5,6]. For the purposes of safety evaluations, the minimum fibrillating current should be used. The Dalziel equation is described as being applicable to shock durations from 8.3 milliseconds (one-half of a 60 Hz) to 5 seconds. Shocks shorter than 8.3 milliseconds are better classified as impulse shocks, which will be discussed separately. Dalziel states [5] that from 5 seconds to 20 or 30 seconds, evidence indicates that the threshold remains fairly steady and may drop only slightly. For longer periods, it is felt that asphyxial changes will exert an increasingly important influence, and may drop the threshold even further.

In summary, from Dalziel's equation the minimum fibrillating current for adults is 116 mA for a 1 second shock and for children is 100 mA for a shock of the same duration. The generally accepted threshold current below which the chance of fibrillation is very slight in man is 100 mA for 60-Hz sine wave shocks for 3 seconds or more [2,9].

There is very little information available on ventricular fibrillation currents that do not have a frequency of 60 Hz or a sinusoidal waveform.

Ferris, et al. [13] investigated the hazards of dc and ac currents in animals and found that the level of dc current required to produce fibrillation was five times greater than the fibrillation level for 60 Hz ac current. It was also postulated that for shock durations of a fraction of a second, the dc/ac ratio for fibrillation would approach unity. Dalziel [8] stated that the dangerous level for 60 Hz fibrillating currents of very short duration would approach the crest value of that current and that the dc/ac ratio would approach 1:1 for short shocks in terms of crest ac current or $\sqrt{2}$:1 for rms ac current. Knickerbocker [19] has collected more recent data using 20 Hz currents and dc currents and found that the dc/ac (rms) fibrillating current ratios for short duration shocks approached 1:1, and not $\sqrt{2}$:1. Knickerbocker also found that for longer duration shocks greater than 1 second, the dc/ac (rms) fibrillating ratios remained constant at 3.7:1 and not at 4.8 - 5.0:1 as previously theorized by Dalziel. Although Knickerbocker's results may be influenced by the fact that he was using 20 Hz currents, which are known to have slightly higher thresholds for both Let-Go and Fibrillation currents, it is probably safer to be more conservative in estimating dangerous current thresholds by using Knickerbocker's dc/ac (rms) ratios to define safe dc currents.

It is generally accepted that the heart is most sensitive to currents with frequencies between 30 and 100 Hz [2,4,13,20]. In this frequency range, the fibrillation threshold is fairly constant and is approximately the same as the thresholds obtained for 50 and 60 Hz currents. For currents with frequencies above and below this range, the fibrillation thresholds begin to rise. Research on currents with frequencies below 30 Hz have shown an increasing fibrillation threshold with decreasing frequency. Ferris, et al. [13] demonstrated that for currents less than 30 Hz, the fibrillation threshold would rise and gradually approach the dc fibrillation threshold which they found to be five times greater than the 60 Hz fibrillation current. Kouwenhoven, et al. [20] also examined low frequency currents and found that the current required to produce fibrillation increased significantly at frequencies below 10 Hz. In fact, it was found in their dog experiments that 2 second duration shocks of 3-4 mA at 2 Hz failed to cause fibrillation when applied directly to the heart, whereas 60 Hz currents of 0.62 mA maximum would cause fibrillation.

As current frequencies increase above 100 Hz, the Fibrillation Thresholds begin to rise similarly to the rise with decreasing frequency below 30 hertz. Kouwenhoven, et al. [20] found that the shock current with a frequency of 1260 Hz which produced fibrillation was 12 times the fibrillation threshold at 60 Hz. Prevost and Battelli [13,25] reported that fibrillation voltages at 2000 Hz were 10 times the comparable voltages at 200 Hz. Geddes and Baker [4,14] also demonstrated that the levels of current required to cause fibrillation increased with increasing frequency. They reported that the current required to produce fibrillation in dogs at 3000 Hz is 22-28 times that at 60 Hz. Studies have also shown that the minimum fibrillating current at frequencies between 150 and 350 Hz is 5 to 40 times the minimum fibrillating current thresholds between 30 and 100 Hz [4]. Thus, both high frequency and low frequency currents are much safer than currents at power line frequencies.

The minimum fibrillating thresholds associated with exposure to alternating currents in combination with direct currents has been assessed only by G. G. Knickerbocker [2,19]. In his dog experiments, the effects of 20 Hz alternating currents and dc currents both alone and in combination were compared using statistical procedures. From his data, he was able to determine predictions for safety for shock durations $\geq$ 0.5 seconds and $\leq$ 0.2 seconds. He does not make any predictions for shock durations between 0.2 and 0.5 seconds. His work led to the following conclusions:

1. For shock durations $\geq$ 0.5 seconds, the risk from exposure to an arbitrary combination of ac and dc current is the same as that associated with an ac shock of the same peak-to-peak current, where the peak-to-peak current is defined as

$$I_{p-p} = \text{the greater of } I_{dc} + \sqrt{2}\ (I_{ac}(\text{rms})), \text{ or} \quad (1)$$

$$2\sqrt{2}\ I_{ac}\ (\text{rms})$$

2. For shock durations $\leq$ 0.20 seconds, the risk of exposure to an arbitrary combination of ac and dc current is the same as that associated with a pure ac shock with the same peak current, where peak current is defined as

$$I_p = I_{dc} + \sqrt{2}\ (I_{ac}\ (\text{rms})). \quad (2)$$

In both cases I_{ac} is the rms value. The peak-to-peak current or peak current is then converted to an rms value (either $I_{p-p}/2\sqrt{2}$ or $I_{peak}/\sqrt{2}$) which is then related to the Dalziel curves and other published data on human shock effects to determine the relative hazard of the current.

Impulse Currents

The hazards due to impulse or surge currents, as in capacitor discharges, has been addressed only by Dalziel and Lee [1,2,5,8,9]. Although the shock intensity for currents at power line frequencies are determined by the crest of the current wave shape and its duration, the hazards due to very short duration shocks with decay time constants less than 0.1 seconds are related to the energy of the shock (in Joules or Watt-seconds), with current magnitude, quantity, and duration being related quantities of secondary importance. Dalziel has also suggested that this energy concept is suitable for evaluating the dangers resulting from short time exposure to power frequency currents as well as to impulse type currents. However, he also states that this analysis is probably not as accurate for power frequency currents as it is for dc pulses. In the Bell System literature, the statement is made that if the energy to which an average adult human is exposed does not exceed 50 Joules, then that shock is not likely to damage the heart [2]. The source of this threshold is not known. Thus, an energy threshold for capacitors of $1/2(CE^2) \leq 50$ Joules and for inductors of $1/2(LI^2) \leq 50$ Joules would be considered nonlethal. Dalziel [1,2,8], using data relating 60 Hz fibrillating currents to shocks of short duration, has derived an equation expressing the acceptable risk for a single, non-oscillatory exponential discharge which states

$$1/2\ (CE^2) \leq 0.054\ (R_b + R_c). \qquad (3)$$

In this equation C is the capacitance in farads, E is the maximum storage energy of the capacitor prior to discharge in volts, R_b is the person's body resistance in ohms, and R_c is the resistance of the circuit excluding the person's body resistance. The equation would also apply to the discharge energy from an inductor. Thus, for a minimum $R_b + R_c$ of 500 ohms, an acceptable discharge energy would be 27 Joules. Dalziel's analysis also shows that single oscillatory discharges of short duration are approximately twice as dangerous as non-oscillatory discharges, thus making the equation of risk

$$1/2\ (CE^2) \leq 0.027\ (R_b + R_c). \qquad (4)$$

Dalziel offers substantial proof for the validity of his equations by comparing his predictions of safety to animal data and reports on 13 human accidents associated with exposure to impulse currents. No information is available in the literature regarding the dangers associated with exposure to repetitive impulse currents.

Electric fences are another form of impulse electric shock, although more of a blend between ac shocks and impulse shocks. An electric fence typically delivers pulse trains of 60 Hz current with a specified on-time and off-time. Underwriter's Laboratories Standards limit the current pulse train to 0.2 seconds duration with an off period of 0.8 seconds. The off period is required to permit a person to release his hold on the fence. During the on period the energy of the pulse train output delivered to a resistance of 500 ohms is limited to 0.25 joules [1,9].

Burn Hazards

Electrical burns result from the contact of body tissue with energized conductors which produces large quantities of heat as current passes through these tissues. Burns will occur only if the temperature of the tissue is raised sufficiently over a long enough duration to cause structural damage [3,24,31]. The degree of burn injury is dependent on (1) the current flow per unit time, (2) the voltage, (3) the area of contact with both the source and the ground and the depth to which the tissue is affected (hence, the volume of the affected tissue), and (4) the length of time of exposure [12,26,31]. If either the current flow is small enough, or the area of contact large enough, or the time of contact short enough, there will be no significant burns [3].

Joule heating can be expressed as the integral with respect to time of the power dissipated by the current over the duration of contact, or $W = \int(I^2R)\ dt = \int(V^2/R)dt$ [22,26,28,30,31]. For steady-state currents and voltages, the time integral becomes simply a multiplication by time, or $W = (I^2R) \cdot t = (V^2/R) \cdot t$. However, these equations do not take into account many other factors which play a role in the biologic system such as physiologic temperature regulation, air temperature, surface temperature, and radiation effects. In addition, as with any other type of biological/electrical interaction, one must have some knowledge of the cross-sectional area of the body elements involved, of the resistances of these body elements, and of the distribution of currents in these body elements [26]. These parameters are rarely known and can usually only be roughly approximated.

Tissue damage has been shown to be secondary to the conversion of electrical to thermal energy [22], and the destruction of tissue is most often associated with protein coagulation [26]. The greater the resistance of the tissue, the greater will be the heat generated by a given current flow. For this reason, bone and skin and (to a lesser degree) muscle will generate more heat with the passage of a given amount of current than will nerves and blood vessels and tissues with higher conductivity [3,12,22,26,28,30]. However, the current flow will also preferentially choose the pathway of least resistance, thus, for the most part, bypassing tissues of high resistance if possible. Since the skin must be traversed in order for the current to flow, it is responsible for almost all of the resistance encountered by the current, and thus is the location of most electrical burn injuries.

Henriques and Moritz [15,16,23,24] have performed one of the most complete studies relating skin surface burns to thermal injury. Through their research, it was found that temperatures above 60°C would result in tissue destruction with exposure times as short as 5 seconds, while temperatures of 51°C would not result in any significant tissue destruction until after 2 minutes of exposure. However, any temperature greater than a few degrees above body temperature could result in tissue damage if contact is sufficiently prolonged. First degree burns (consisting principally of hyperemia without actual tissue destruction) could be produced by exposure of the skin to 50°C for 20 seconds, but no definite evidence of epidermal injury could be found until after 2 minutes of exposure. As a result of this work, Henriques and Moritz have established a plot of time-surface temperature thresholds at which cutaneous burning (greater than first-degree burns) occurs [24]. This threshold chart has since been used by many subsequent authors as a basis for estimating burn potentials. Henriques and Moritz also demonstrated that repeated subthreshold thermal exposures were cumulative over the first 24 hours and would result in approximately the same degree of thermal damage as would occur with continuous exposure to the same amount of thermal energy.

In estimating the burn potential of electrical contacts, R. K. Wright and J. H. Davis [31] utilize the fact that 1 watt-second (or 1 joule) of energy generates 0.24 calories of heat in water and then appoximate the heat capacity and density of skin by that of water ($1^{o}C \cdot g/calorie \times 1\ cm^{3}/g$). Assuming two one cm^2 contact points (one energized and one grounded) and assuming that heating of the skin is concentrated below those contact points to a depth of 1 cm, one can then calculate the rise in skin temperature associated with a given electrical contact using the formula Temperature in ^{o}C = Energy x (0.24 calories/joule) x ($1^{o}C \cdot g/calorie$) x ($1\ cm^3/g$) $\div$ ($2\ cm^3$ Volume). For example, the minimum energy associated with the minimum fibrillation current at 60 Hz would be 1.0 watt-seconds ($W = I^2Rt \cong (0.1A)^2 \times (1000\Omega) \times (0.1\ seconds) = 1.0$ joules). This amount of energy would only be sufficient to raise the surface temperature of the described 2 cm^3 volume of skin (approximated by a 2 cm^3 volume of water) by $0.12^{o}C$ which would be insufficient to cause any burns. Damage resulting from surface burns is most often found at the interface between the epidermis and the dermis (approximately 80 microns below the skin surface) [23,24,26]. Because of the higher resistance of the skin relative to internal body fluids, most of the heat production secondary to current flow will occur in the skin. Burns of the deep tissues will occur only with energies greater than that required to char the skin (temperatures greater than $65^{o}C$ for longer than 10 minutes). Thus, the model for skin heating as described above is useful for estimating surface burn hazards of low energy electrical contacts since it assumes the current will seek the lower resistance pathways through the deeper body fluids below the surface of the skin. These low resistance pathways will then tend to form a "short circuit" between the two skin surface contacts. Although this model is fairly conservative by confining the area of heating only to the volume of skin directly below the surface contact area, the depth of heat concentration might be better approximated by the actual depth of the epidermis and dermis which is experiencing the heat damage, especially when examining fingertip and hand contact. For humans, this skin depth tends to average between 1-2 mm. Using this approximation for the depth of heating, the temperature rise resulting from two 1 cm^2 electrical contacts as previously described would be 0.6 -$1.2^{o}C$

which is still inadequate to produce substantial surface burns. Both models of the skin will tend to overstate the possibility of surface burns since current in contact with the body tissues will most likely distribute over a larger volume of tissue than that directly underlying the surface contacts. In addition, it should be noted that for almost any amount of thermal energy, a small enough area of contact can be selected such that the possibility of a surface burn will be high. Thus, fingertip or spark gap type contacts will often generate a small burn whereas the same amount of energy over a larger surface area would be barely enough to redden the skin.

Evaluation of the Safe Case

Designs #1 and #2

In evaluating the safety of this device, the voltage output across several resistances was measured using a high voltage probe (x 1000). Resistances were selected for testing between 500 ohms and 1,000,000 ohms in order to represent the full range of possible human body resistances as reported in the literature. The resistances tested were 220Ω, 470Ω, 1kΩ, 10KΩ, 100KΩ, and 1MΩ. From these measurements the current could then be calculated and compared to the known limits of current safety discussed previously. Safe Case Designs #1 and #2 had almost identical results except that the peak voltage and energy output from Design #2 was slightly higher than #1. The following discussion will refer mainly to results from Design #1; however, in general the conclusions will apply to both designs.

The voltage waveform across each resistance was a single spike with an exponential decay that repeated approximately every second. The data collected for each resistive load is summarized in Table 2, which lists the maximum measured voltage (V_{max}), the calculated maximum current (I_{max}), the decay time constant of the spike (τ), the time between spikes, the associated frequency of the discharge, the calculated energy of each spike (W), and the associated temperature rise that might be expected for each spike.

Figure 2 displays graphically both the current (2-a) and the voltage (2-b) as the resistance increases. In addition, the current graph (2-a) also shows several reported threshold levels for comparison. These levels will be discussed shortly. The energy content of each spike was calculated by modeling the impulse as an exponential function that reaches V_{max} (or I_{max})

TABLE 2

SAFE CASE #1 - MEASURED AND CALCULATED PARAMETERS FOR EACH TEST LOAD

Load	V_{max}	I_{max}	Spike τ ($V=0.368\ V_{max}$)	Repetition Rate	Frequency	Spike Energy ($W = \frac{V_o^2}{R} \cdot \frac{\tau}{2}$)	Temperature Rise ($^{o}C \cdot cm^3$/spike
220Ω	225V	1.025A	0.80 msec	1.0 sec	1 Hz	92×10^{-3} joules	22.08×10^{-3}
470Ω	400V	0.85A	0.70 msec	1.0 sec	1 Hz	119×10^{-3} joules	28.56×10^{-3}
1000Ω	700V	0.70A	0.60 msec	1.0 sec	1 Hz	147×10^{-3} joules	35.28×10^{-3}
10KΩ	1200V	0.12A	0.60 msec	1.0 sec	1 Hz	43×10^{-3} joules	10.32×10^{-3}
100KΩ	1250V	0.0125A	.55 msec	0.9 sec	1.1 Hz	4.3×10^{-3} joules	1.03×10^{-3}
1MΩ	1220V	0.00122A	.55 msec	0.9 sec	1.1 Hz	0.41×10^{-3} joules	0.099×10^{-3}

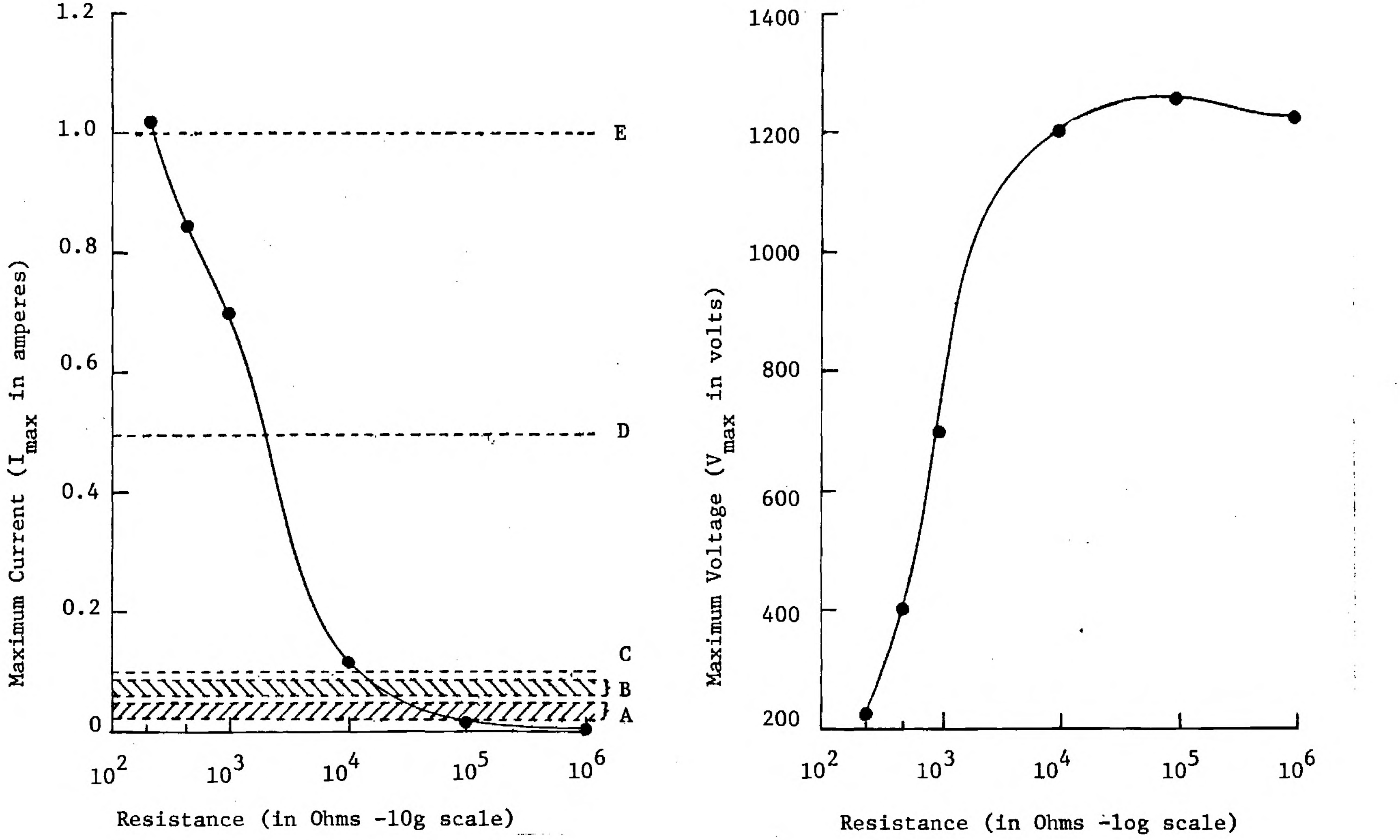

Figure 2. (a) Maximum Current (I_{max}) and (b) Maximum Voltage (V_{max}) of the Impulse Shock Produced by Safe Case #1 as a Function of Resistance. Figures 2(a) also Shows Several Thresholds of Safety for Purposes of Comparison: A. 5 Hz Let-Go Thresholds Determined by Dalziel [11], B. D.C. "Release Thresholds" Determined by Dalziel [11], C. 60 Hz Fibrillation Threshold for a 3 Second Shock for an Adult Male, D. D.C. Fibrillation Threshold for a Continuous Exposure Duration of 0.1 - 1.0 Seconds, E. Fibrillation Threshold for a Single Current Pulse of Less than 10 msec. Duration (Either DC or 60 Hz) [2].

instantaneously and then decays with time constant τ. Hence, $V = V_{max} e^{-t/\tau}$ for $t \geq 0$. Using the energy equation, $W = \int_0^t (V^2/R)\, dt$, the energy of this spike would be $W = \frac{(V_{max})^2}{R} \cdot \frac{\tau}{2} \cdot (1-e^{-2t/\tau})$. For $t > 5\tau$, as is the case for spikes occurring approximately every second, $e^{-2t/\tau} \simeq 0$ so the energy equation becomes $W = \frac{(V_{max})^2}{R} \cdot \frac{\tau}{2}$.

As resistance increases, the voltage increases until a maximum voltage of 1250 V is achieved for resistances greater than 10KΩ. Current, on the other hand, is maximal at low resistances and decreases as resistance increases. As the resistance increases beyond 10KΩ, the current approaches zero and soon drops below the range of biological effects. As can be seen from Table 2, the frequency of repetition of the spike discharge is about 1 Hertz (Hz). Unfortunately, there is no data reported in the literature concerning currents with a frequency of 1 Hz. There is also no data in the literature regarding the effects of repeated exposure to impulse discharges at this frequency. According to Dalziel [8], an average man should be able to tolerate a single impulse shock of as much as 27 joules without any appreciable risk, yet there is no mention made of repeated exposures. Ferris, et al. [13], found no cumulative effect on the ventricular fibrillation threshold with successive subthreshold shocks of 0.03 to 0.1 second duration, but these shocks were only administered at 5 minute intervals. Thus, the heart is evidently able to recover from successive subthreshold shocks providing there is 5 minutes between shocks. Spear, et al. [27] found that the heart was more susceptible to fibrillation after a train of pulses than after a single pulse; however, the pulse trains consisted of pulses at a frequency of 100 Hz and these results could be simply related to Dalziel's findings of increasing susceptibility to fibrillation with increasing duration of exposure to power line currents. Kouwenhoven [20] examined 2 second shocks at a frequency of 2 Hz applied directly to the canine heart and was unable to cause fibrillation even at currents 5-6 times greater than the fibrillation threshold at 60 Hz. The 2 Hz current used was an interrupted direct current that had an on:off ratio of 1:1. The Fibrillation Threshold for dc currents with a duration between 0.1 and 1.0 seconds is commonly given as approximately 500 mA [2] and is illustrated on Figure 2(a) by dotted line D. For dc currents of less than 0.1 second duration, the threshold increases with decreasing duration in a 1:1 ratio (or $\sqrt{2}$:1 ratio according to Dalziel) with the threshold for 60 Hz currents for shocks of less than 0.1 second duration. For an exposure duration of 10 msec, the Fibrillation Threshold is given as 1 ampere [2,6,8,9] (illustrated in Figure 2(a) by dotted line E). However, this value is valid only for single shocks.

The current impulse produced by Safe Case Design #1 is relatively safe when looked at as a single impulse. Its theoretical maximum energy output of 0.16 joules ($W = 1/2\left(CV^2\right)$) is close to the actual measured maximum value at 1KΩ of 0.147 joules and is definitely much less than Dalziel's acceptable energy surge of 27 joules. The decay time constant never exceeds 1 msec, so the maximal measured current of 1.02 A at 220Ω compares favorably with the Fibrillation Threshold of 1.0 A for a current pulse of 10 msec duration. In addition, this resistance of 220Ω is less than Dalziel's recommended minimum of 500 Ω for the human body resistance. However, it must be assumed that a criminal trying to steal a case of money will not be easily deterred by a single current impulse and will try to hold onto the case over at least several current impulses. At this point, the frequency of the current impulses will begin to play a major role in determining the threshold of safety. The dc Fibrillation Threshold for durations between 0.1 and 1.0 seconds as illustrated by line D in Figure 2(a) will most probably be a very generous estimate for the minimum fibrillation threshold of an exposure to any type of current at a frequency of 1 Hz. As can be seen by Figure 2(a), the currents produced by Design #1 are consistently above this threshold for resistances less than approximately 2500 ohms.

The effect of waveform on Fibrillation Thresholds has never been adequately assessed in the literature. Kouwenhoven, et al. [20] found that interrupted direct current (similar to a square wave) was more likely to cause fibrillation than was a sinusoidal current at the same peak intensity, but the reason for this phenomenon was never elucidated. Dalziel [10] has examined the effect of waveform on Let-Go Thresholds and found the threshold to be mainly a function of peak current and relatively independent of the waveform itself. One is therefore inclined to extend this finding to Fibrillation Thresholds and state that these, too, are dependent only on peak current. Nevertheless, the available literature does not provide support for any theories of the effect of waveform on the safety of currents.

The energy content of each spike was maximal across a resistance of 1KΩ with a value of 0.147 joules which compares favorably with the theoretical maximal energy storage due to the capacitor of 0.16 joules. This value is also well within the safety limits established by Underwriter's Laboratories for electric fences [1]. Figure 3 displays the spike energy as a function of resistance and shows how the energy content decreases for both resistances greater than and less than 1KΩ. The theoretical temperature rise resulting from the energy of each spike is adapted from the estimation of burn potential proposed by Wright and Davis [31]. The temperature rise as given in Table 2 is given in units of $^{o}C - cm^{3}$/spike and can be adapted to any desired tissue model after dividing by the proposed volume of the tissue being heated. The maximal calculated temperature rise is given for a resistance of 1KΩ as 0.0353 $^{o}C - cm^{3}$/spike. Using the Wright and Davis model of two 1 cm^{3} volumes of skin in conjunction with the Henriques and Moritz chart of time and surface temperature thresholds for cutaneous burns, a person would have to hold onto the activated Safe Case #1 for more than 700 seconds before suffering anything more than first-degree burns. If heating of the skin is confined to a depth of 1 mm, the temperature rise will be 10 times greater and the perpetrator would have to hold onto the case for more than 80 seconds to achieve the same degree of burn. Even two fingertip contacts of, say, 1 mm x 1 mm each heated to a depth of 1 mm would only result in second degree burns after 3 seconds. Thus, the burn potential is extremely low.

Similar measurements and analysis were made on Safe Case Design #2. The shock delivery mechanism of Design #2 was virtually identical to Design #1 except for a slight change in the transformer turns ratio and the addition of an increased capacitance which increased the theoretical energy content of the discharge to 0.25 joules. As with Design #1, this energy limitation is within the energy criteria established by Underwriter's Laboratories for electric fences. Other than the increased values of voltage, current, and spike energy content, the results overall were virtually identical to that of Design #1. However, the current spikes for low resistances were at more dangerous levels than Design #1. Because of the similar results and conclusions, the data on Design #2 will not be presented.

Both Design #1 and #2 had difficulty meeting safety threshold levels for low values of resistance. Design #1 demonstrated a problem at increased

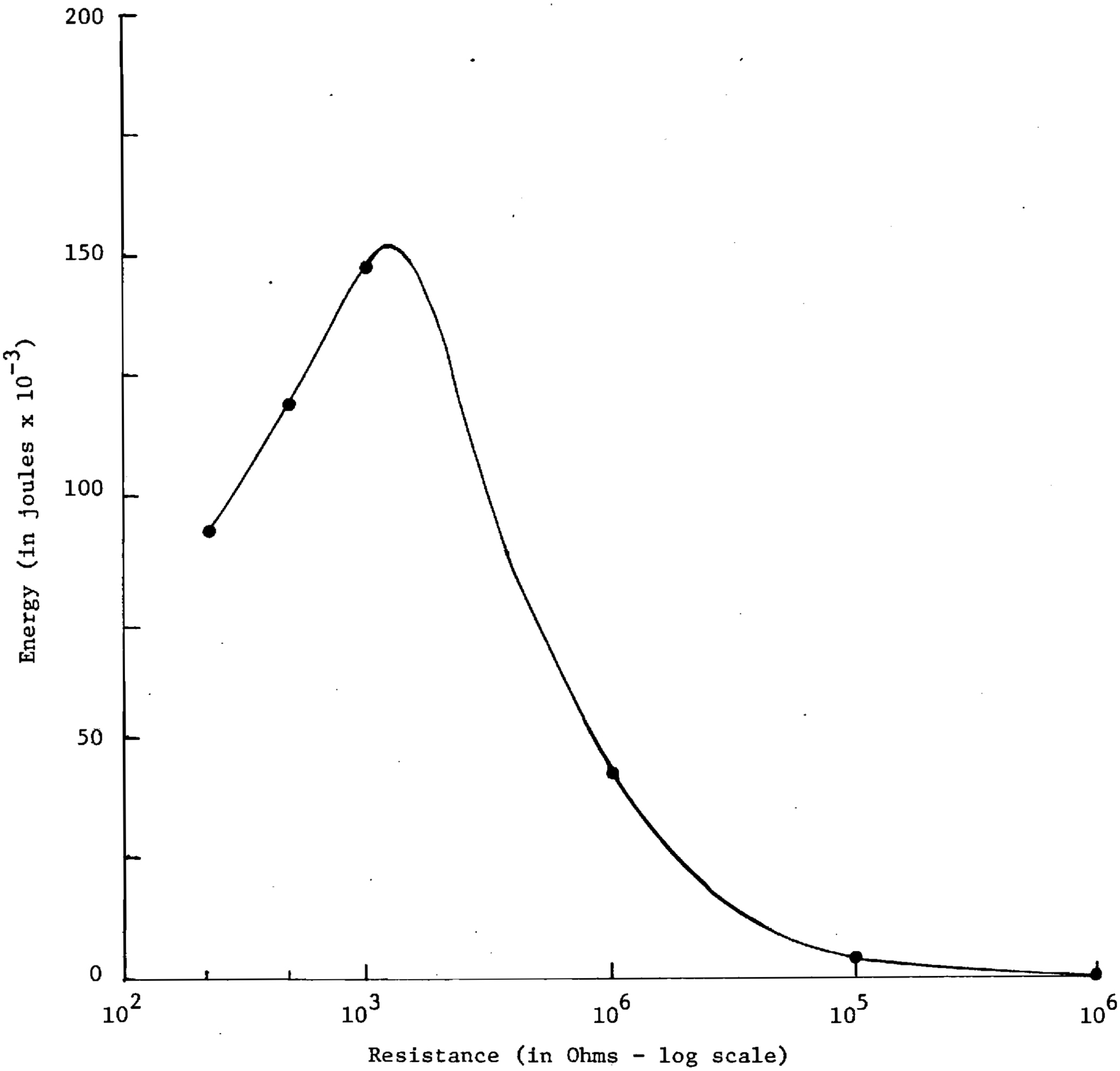

Figure 3. Estimated Energy per Impulse Spike as a Function of Resistance for Safe Case Design #1.

resistances since the current would have very little shock potential for callous skin with impedances greater than 10KΩ. In addition, at low resistances the currents produced were very close to exceeding the ventricular fibrillation thresholds. Design #2 with its increased energy output and higher overall currents had improved shock potential at higher impedances, but also exceeded safety thresholds at low impedances. Neither design was felt to be entirely safe because of the high currents produced at low resistances.

At this point, it will be helpful to describe in greater detail the effects of contact area on shock. Skin impedance, in addition to varying widely between individuals and with environmental conditions, will also vary inversely with the area of electrical contact. For fingertip contacts, the area of contact will be small, so the total resistance due to skin will be large. Because of this small contact area and large impedance, several electrical shock parameters will be affected. The high impedance will tend to limit the magnitude of the currents produced by the contact such that very little current is available to travel to the heart and cause fibrillation. The high impedance and small contact area will also increase the potential for surface burns as was just demonstrated. This is why most high energy electrical burns associated with brushing contacts are characterized only by pinhole burns of the skin surface. Finally, with small areas of contact, the current density will be higher and the perception of current will be more acute. A person attempting to steal the Safe Case will possibly try to decrease the painful effects by increasing the contact area and lowering the skin resistance by gripping the handle more tightly. Should this happen, the resistive component due to skin will be decreased and thus more current will flow into the deeper tissues. By gripping the handle tighter,a person will decrease his sensitivity to the current and his potential for surface burns at the risk of predisposing himself to deep tissue (e.g. muscle) heating and to the possible fibrillation effects of the current. An ideal shocking device would be a type of constant current device that would deliver a fairly constant current intensity over the range of human body resistances. As will be seen, Design #3 comes very close to meeting this ideal.

Design #3

As with Designs #1 and #2, Safe Case Design #3 was evaluated by measurements of the voltage waveform produced across a number of different resistances between 500 ohms and 1,000,000 ohms. The resistances selected were 500Ω, 1KΩ, 10KΩ, 100KΩ, and 1MΩ and were chosen to represent the full range of reported human body resistances in the literature. From these voltage measurements, current could then be calculated and compared to reported limits of current safety.

The Safe Case produced a variety of different waveforms depending on the resistance being tested. These waveforms are displayed in the photographs in Figures 4-8. The waveforms can be best described as resembling those of a capacitor discharging repetitively at a high frequency. The data collected for each resistive load is summarized in Table 3, which lists the voltage range, the current range, the period between individual discharges, the frequency of discharges, the decay time constant of the discharge spike, the duration of time that the pulse train was on, and the duration of time that the pulse train was off. Voltage and current ranges are given from peak-to-peak (V_{p-p} and I_{p-p}). It should be noted that for low resistive loads (500Ω and 1000Ω), the pulse train in general showed an initially positive displacement with a lower frequency waveform which would rapidly decay to a baseline higher frequency waveform. Thus, the waveform is described in two parts: (1) the V_{p-p}, I_{p-p}, and period of the first observed spike waveform, and (2) the V_{p-p}, I_{p-p}, and period of the baseline waveform. The two different frequencies given for each of these low resistance loads are derived from their respective periods. For the high resistance loads (100KΩ and 1MΩ), the waveform was constant and did not show the variation observed with the low resistance loads. The waveform for the 10KΩ resistance was intermediate between the high and low resistance waveforms and showed only a small insignificant amount of variation.

In general, the peak-to-peak voltages showed large increases with increasing resistance. The peak-to-peak currents tended to decrease with increasing resistance and are illustrated graphically in Figure 9. At low resistances the current seems to be asymptotically limited. The current also remarkably retains a fairly constant value over the entire tested range of resistance until after 100KΩ when it begins to drop rapidly. The frequency of

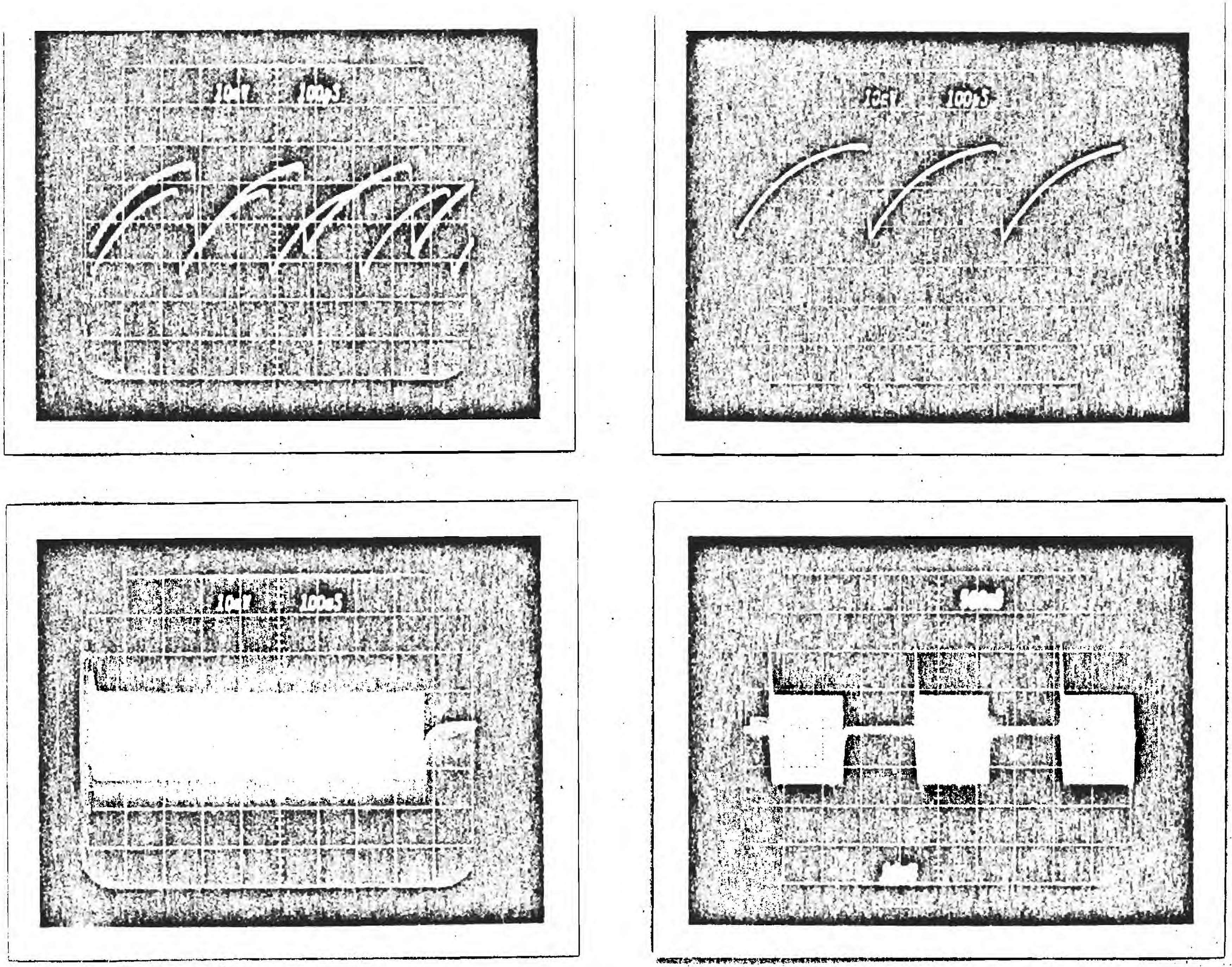

Figure 4. Voltage Waveforms Produced by the Brink's Safe Case Design #3 Across a 500 Ohm Resistance (Measured Using a 1000 x High Voltage Probe).

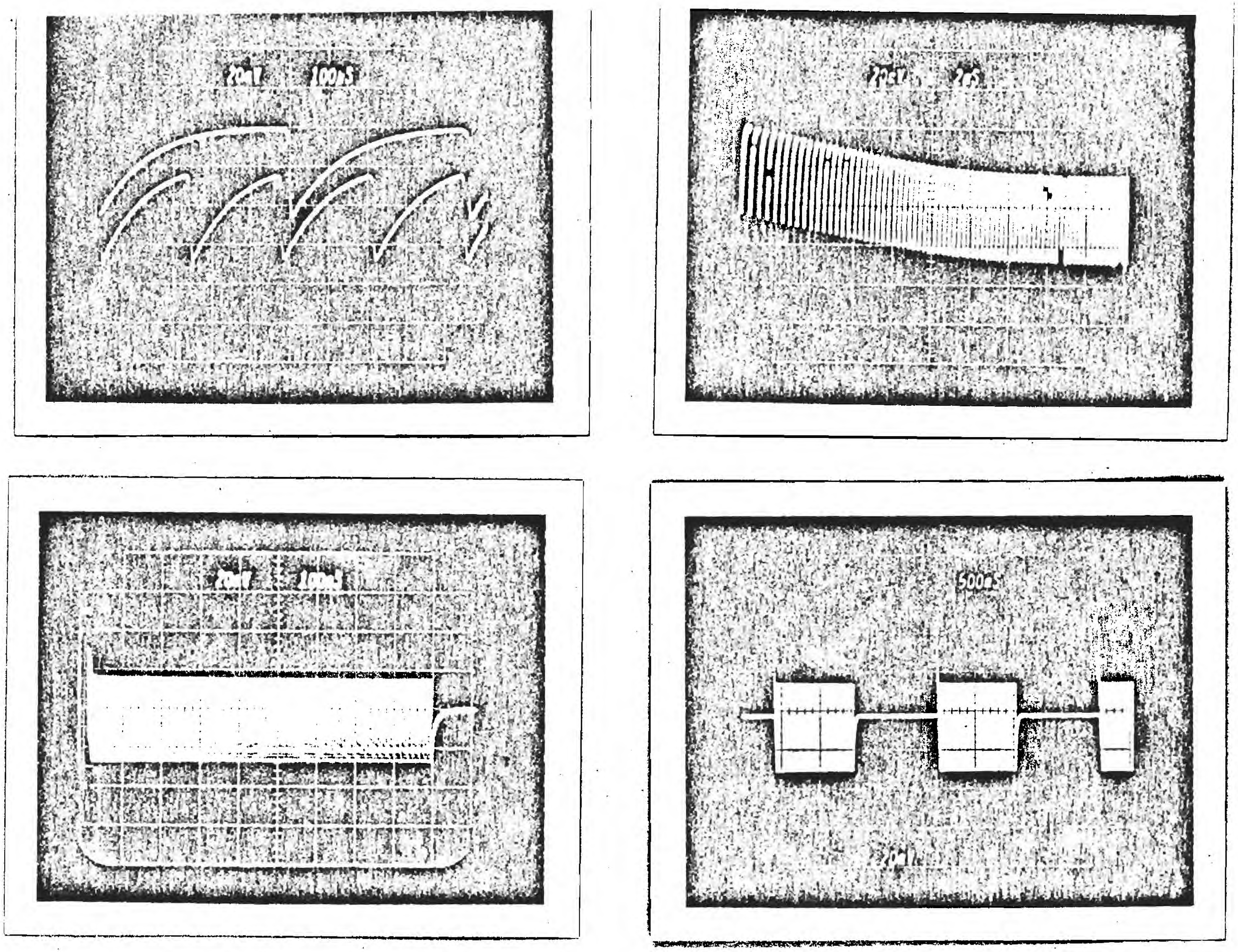

Figure 5. Voltage Waveforms Produced by the Brink's Safe Case Design #3 Across a 1000 Ohm Resistance (Measured Using a 1000 x High Voltage Probe).

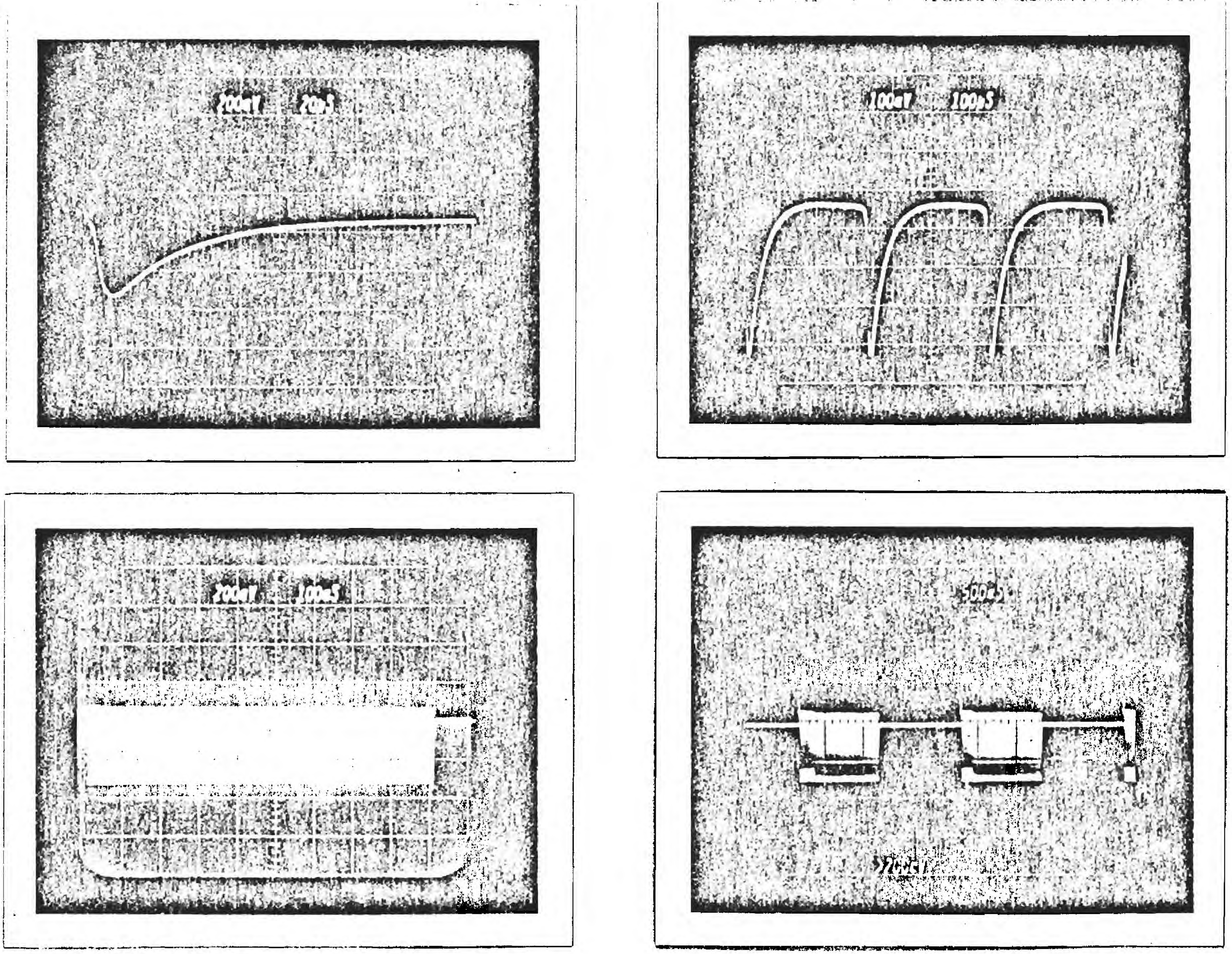

Figure 6. Voltage Waveforms Produced by the Brink's Safe Case Design #3 Across a 10,000 Ohm Resistance (Measured Using a 1000 x High Voltage Probe).

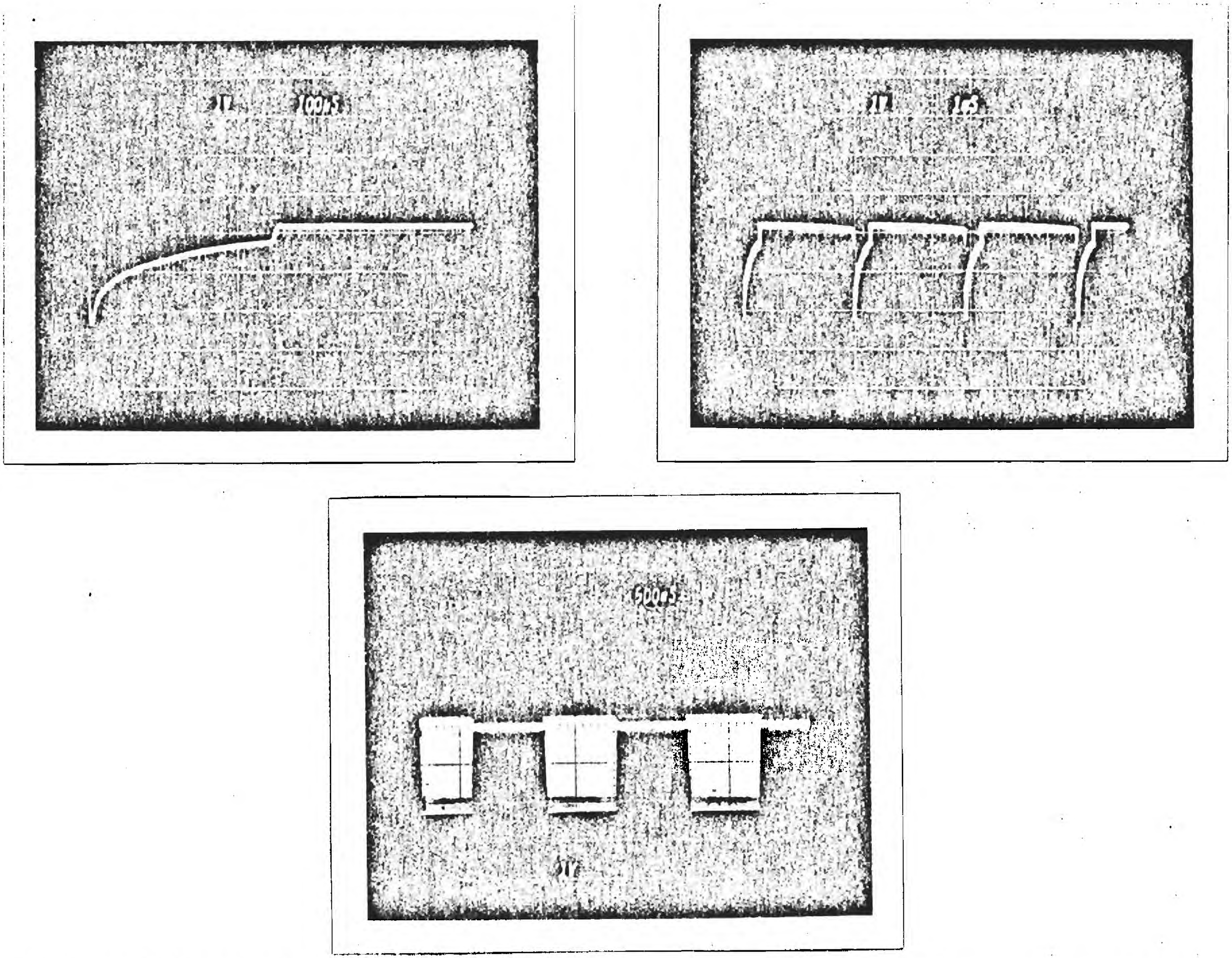

Figure 7. Voltage Waveforms Produced by the Brink's Safe Case Design #3 Across a 100,000 Ohm Resistance (Measured Using a 1000 x High Voltage Probe).

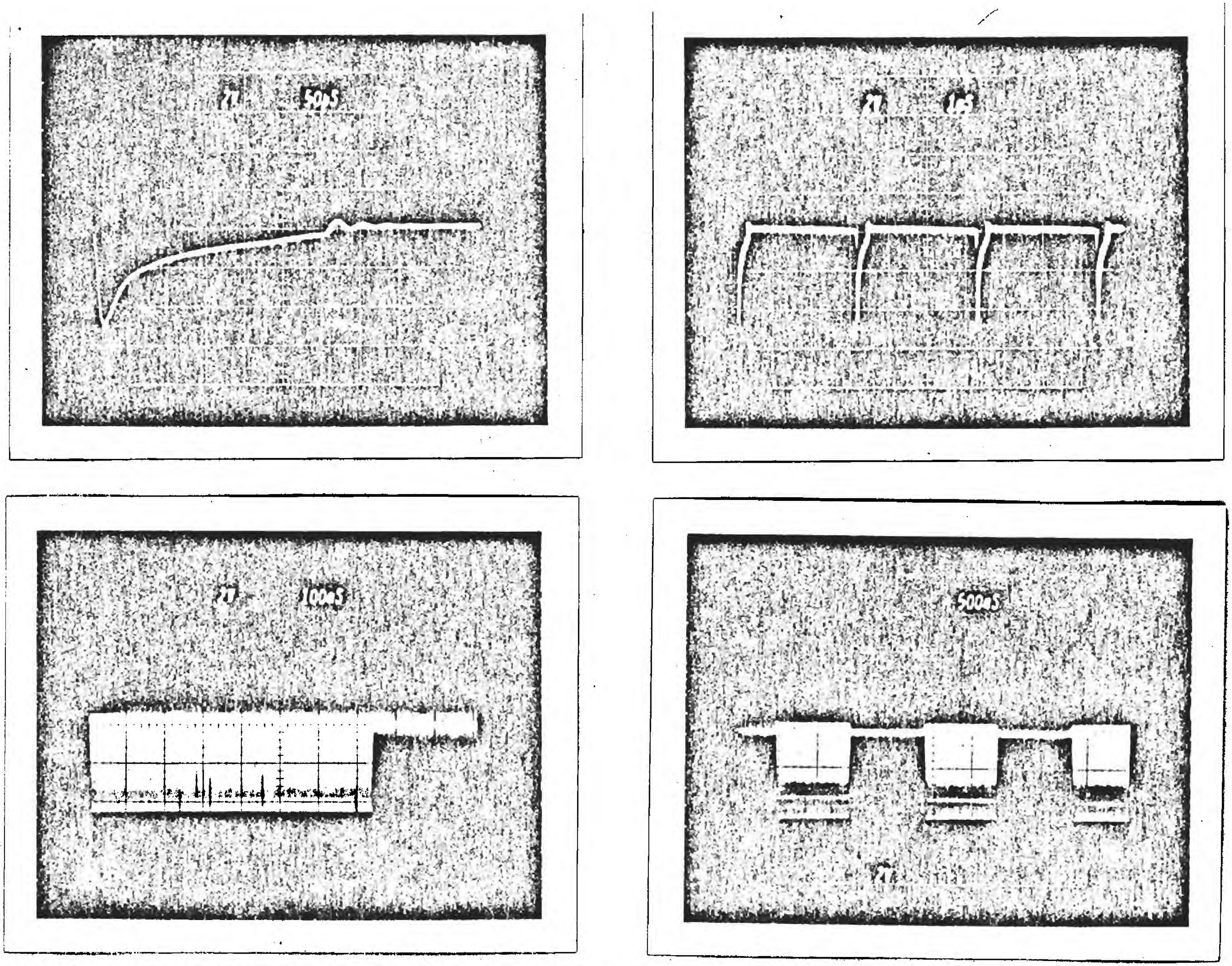

Figure 8. Voltage Waveforms Produced by the Brink's Safe Case Design #3 a 1,000,000 Ohm Resistance (Measured Using a 1000 x High Voltage Probe).

TABLE 3

MEASURED PARAMETERS FOR EACH TEST LOAD

(Safe Case #3)

[illegible]	[illegible]	[illegible]	Period	Freq.	Spike τ ($V=0.368\ V_{max}$)	Pulse Train On	Pulse Train Off	Pulse Train Period	Pulse Train Freq.
			msec msec	2857 Hz 4348 Hz	130 msec 110 msec	0.03 sec 0.97 sec 1.00 sec	1.0 sec	2.0 sec	0.5 Hz
			) msec } msec	2000 Hz 4348 Hz	130 msec 110 msec	0.03 sec 1.02 sec 1.05 sec	1.1 sec	2.15 cc	0.47 Hz
10 kΩ	(-330 - +60V)	(-33 - +6)	2 msec	3125 Hz	52 msec	1.0 sec	1.1 sec	2.1 sec	0.48 Hz
100kΩ	-2400 - +200V	-24 - +2 mA	2.9 msec	345 Hz	200 msec	0.9 sec	1.0 sec	1.9 sec	0.53 Hz
1MΩ	-5000 = +400V	-5 - +0.4 mA	3.1 msec	323 Hz	100 msec	0.9 sec	1.0 sec	1.9 sec	0.53 Hz

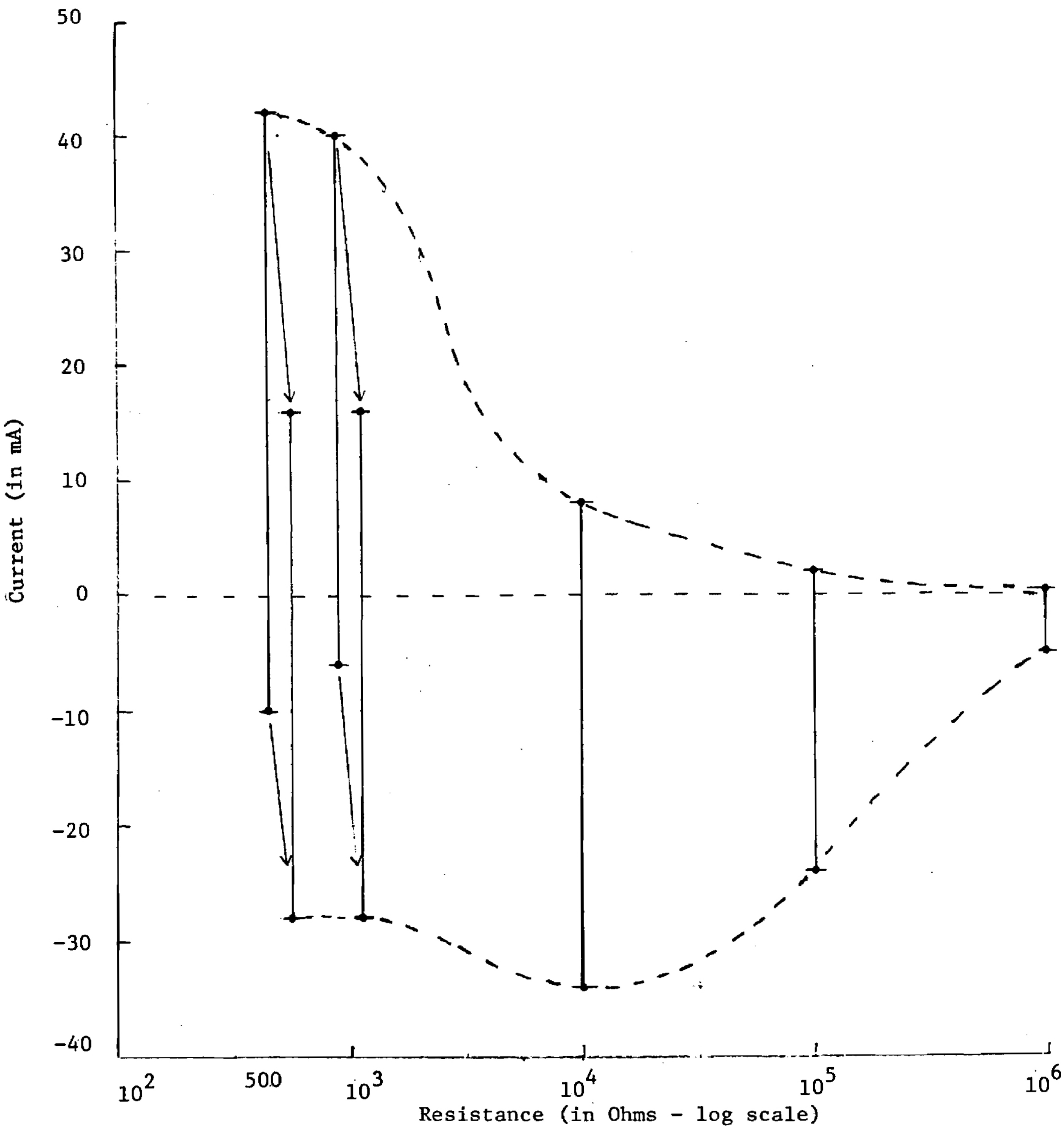

Figure 9. Current Amplitude Bounds of Waveforms Produced by Safe Case Design #3 vs. the Tested Resistances. Note the Changes in Current Amplitude for the Low Resistances from Initial to Baseline Values.

the produced waveform as a function of resistance is shown in Figure 10. The frequency response is roughly sigmoidal being limited to 4350 Hz at lower resistances and to 320 Hz at higher resistances. The frequency change is greatest between resistance values of 10KΩ and 100KΩ.

Because of the lack of available information on exposure to repetitive impulse currents, an analysis of the safety of the Brink's Safe Case Design #3 was felt to be inadequate when based solely on Dalziel's definition of safety for single impulse currents. Thus, our analysis consisted of an adaptation of G. G. Knickerbocker's equation [2,19] for evaluating the safety of combinations of ac and dc currents. The analysis of the Brink's Safe Case waveform consisted of first modeling the current waveform as a sinusoidal current, then breaking this current model into its dc and ac components and applying Knickerbocker's equations for duration ≥ 0.5 seconds (since all pulse train durations were ≥ 0.5 seconds) to obtain an equivalent ac rms current which could then be compared to the adaptation of the Dalziel graphs in Figure 1.

The first sinusoidal model used was obtained by setting the I_{p-p} of the sinusoidal model equal to the I_{p-p} of the measured current ($I_{p-p} = I_{HIGH} - I_{LOW}$) and then determining the dc current as half of the peak-to-peak current ($I_{dc} = 1/2\ (I_{HIGH} - I_{LOW})$). Figure 11 is a sketch of the sinusoidal model superimposed on the measured waveform for each resistance. Table 4 lists the calculations involved in interpreting this model and the equivalent rms ac currents this model represents. These results are then plotted on the adapted Dalziel curves in Figure 12 and are found to all lie below the 99.5 percentile line for the Let-Go Threshold.

Although this approximation is felt to be conservative, there was some concern that since we are dealing with the safety of individuals the model was not conservative enough. In light of the fact that most effects of current are related to the crest of the current wave [2,7,10,26], it was decided to evaluate another more conservative model. In the second model evaluated, the sinusoidal signal evaluated was given the same peak current ($I_{PEAK} = \sqrt{2}\ I_{ac}(rms)$) as the measured waveform's peak-to-peak current ($I_{p-p} = I_{HIGH} - I_{LOW}$) while the dc part of the current was set at the most positive part of the waveform ($I_{DC} = I_{HIGH}$). A sketch of this second sinusoidal model is depicted in Figure 13 superimposed on sketches of the actual measured waveform for each resistance. As one can see, this is an extremely conservative model for the

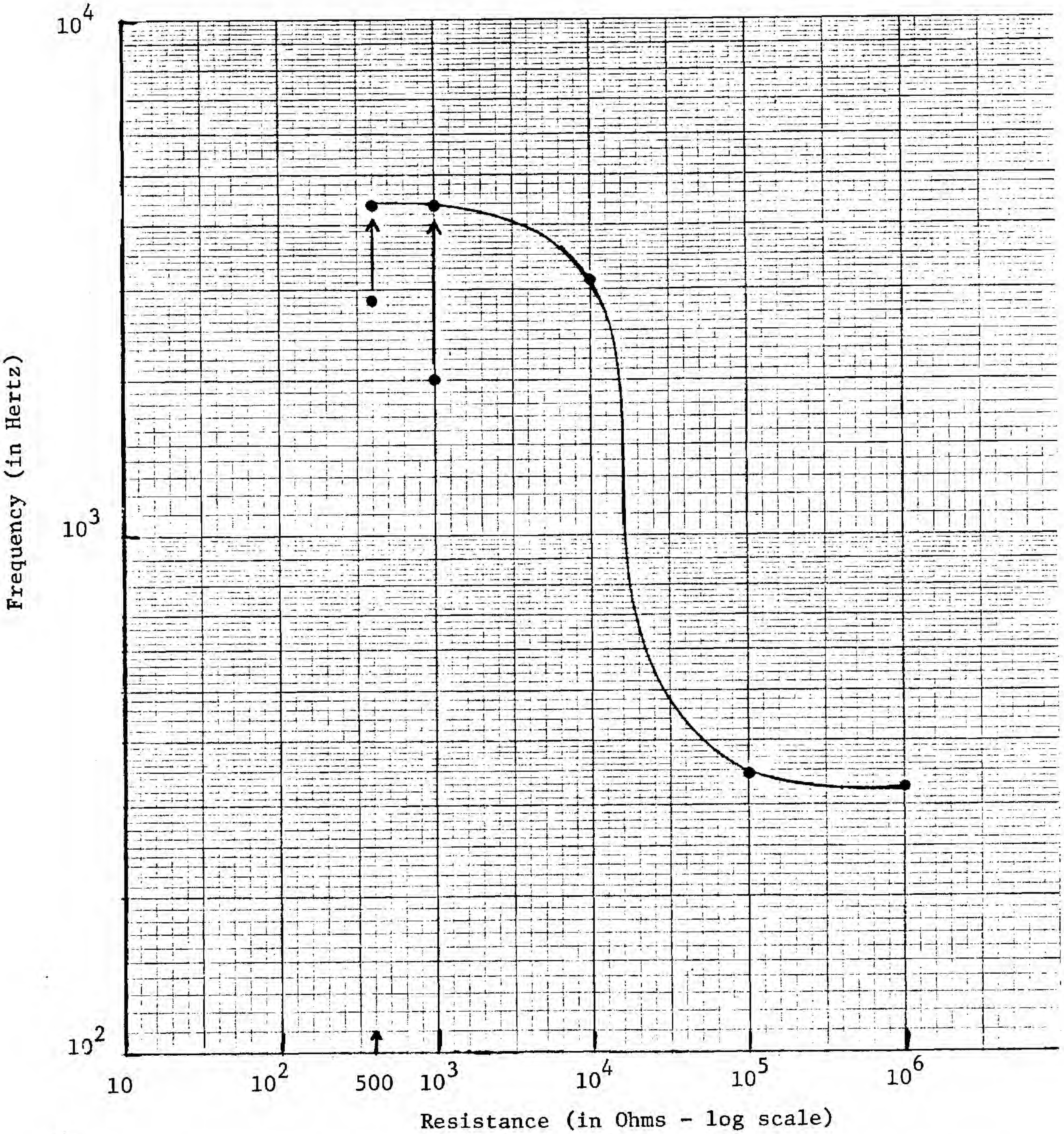

Figure 10. Frequency of Waveforms Produced by Safe Case Design #3 vs. the Tested Resistances. Note the Changes in Frequency for the Low Resistances from Initial to Baseline Values.

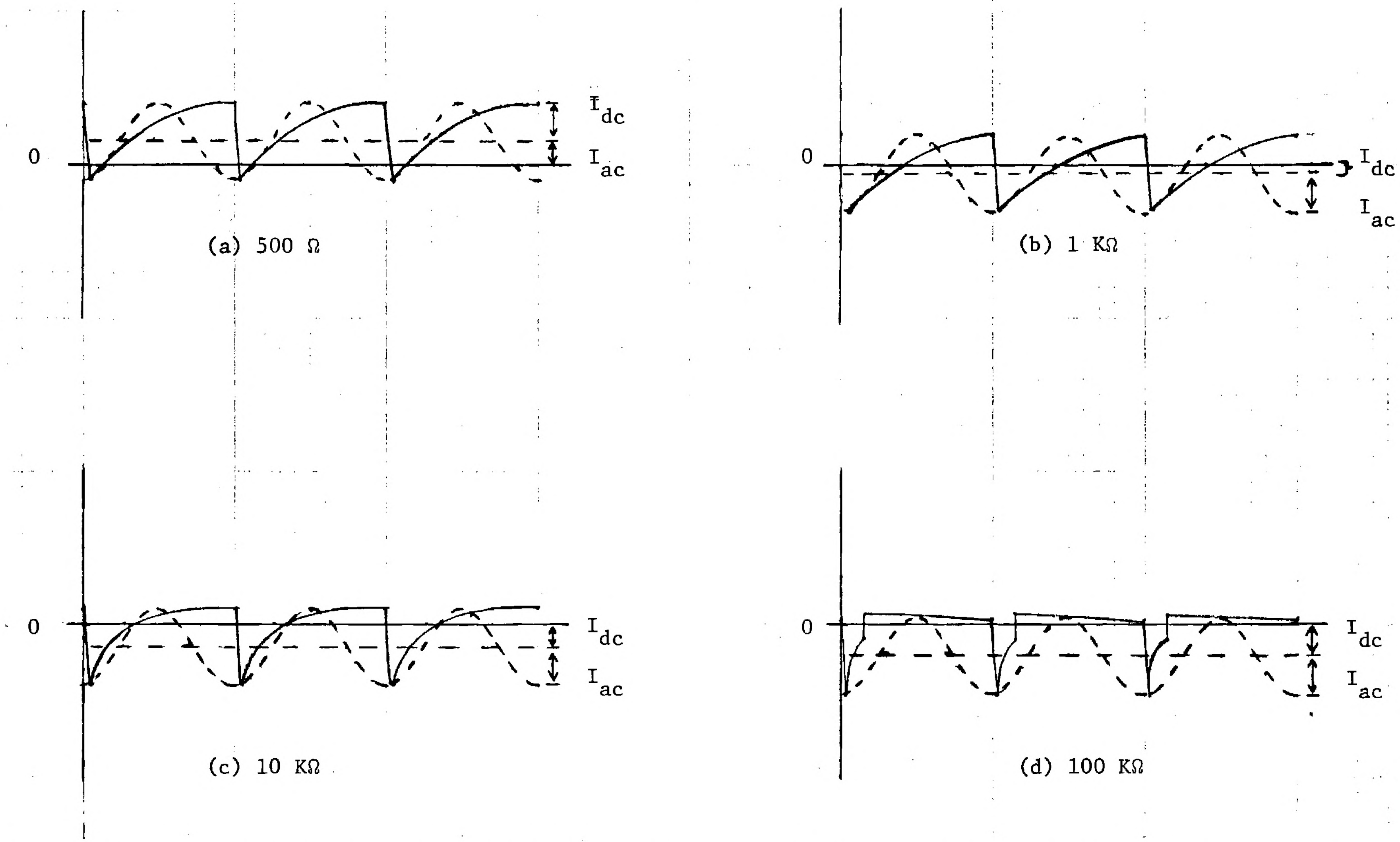

Figure 11. Sketch of the First Sinusoidal Model Used for the Evaluation of Waveform Safety Superimposed on Reproductions of the Measured Waveforms for Each of the Resistances Tested. The Waveform for the 1MΩ Resistance is Almost Identical to that for the 100 KΩ Resistance. The Value for I_{dc} is Obtained as Shown, While the Value for I_{ac} is Converted to RMS.

TABLE 4

CALCULATIONS USED TO ESTIMATE THE EQUIVALENT SINUSOIDAL CURRENT

FOR PURPOSES OF COMPARING TO KNOWN SAFETY VALUES*

METHOD #1

Load	I_{dc}	$\lvert I_{ac}\ (\mathrm{peak})\rvert$ ($=\sqrt{2}\ I_{ac}$)	$I_{dc} + \sqrt{2}\ I_{ac}$	$2\sqrt{2}\ I_{ac}$	Equivalent I_{ac} (rms)	Frequency
500 Ω	+16 mA	26 mA	42 mA	52 mA	18.6 mA	2857 Hz
	-6 mA	22 mA	28 mA	44 mA	15.6 mA	4348 Hz
1000 Ω	+17 mA	23 mA	40 mA	46 mA	16.3 mA	2000 Hz
	-6 mA	22 mA	28 mA	44 mA	15.6 mA	4348 Hz
10 KΩ	-13 mA	21 mA	34 mA	42 mA	14.9 mA	3125 Hz
	(-13.5 mA)	(19.5 mA)	(33 mA)	(39 mA)	(13.8 mA)	
100 KΩ	-11 mA	13 mA	24 mA	26 mA	9.2 mA	345 Hz
1 MΩ	-23 mA	2.7 mA	5 mA	5.4 mA	1.9 mA	323 Hz

*Calculations are based on modeling the measured current as a sinusoidal current with the same I_{p-p} as the measured current's I_{p-p}.

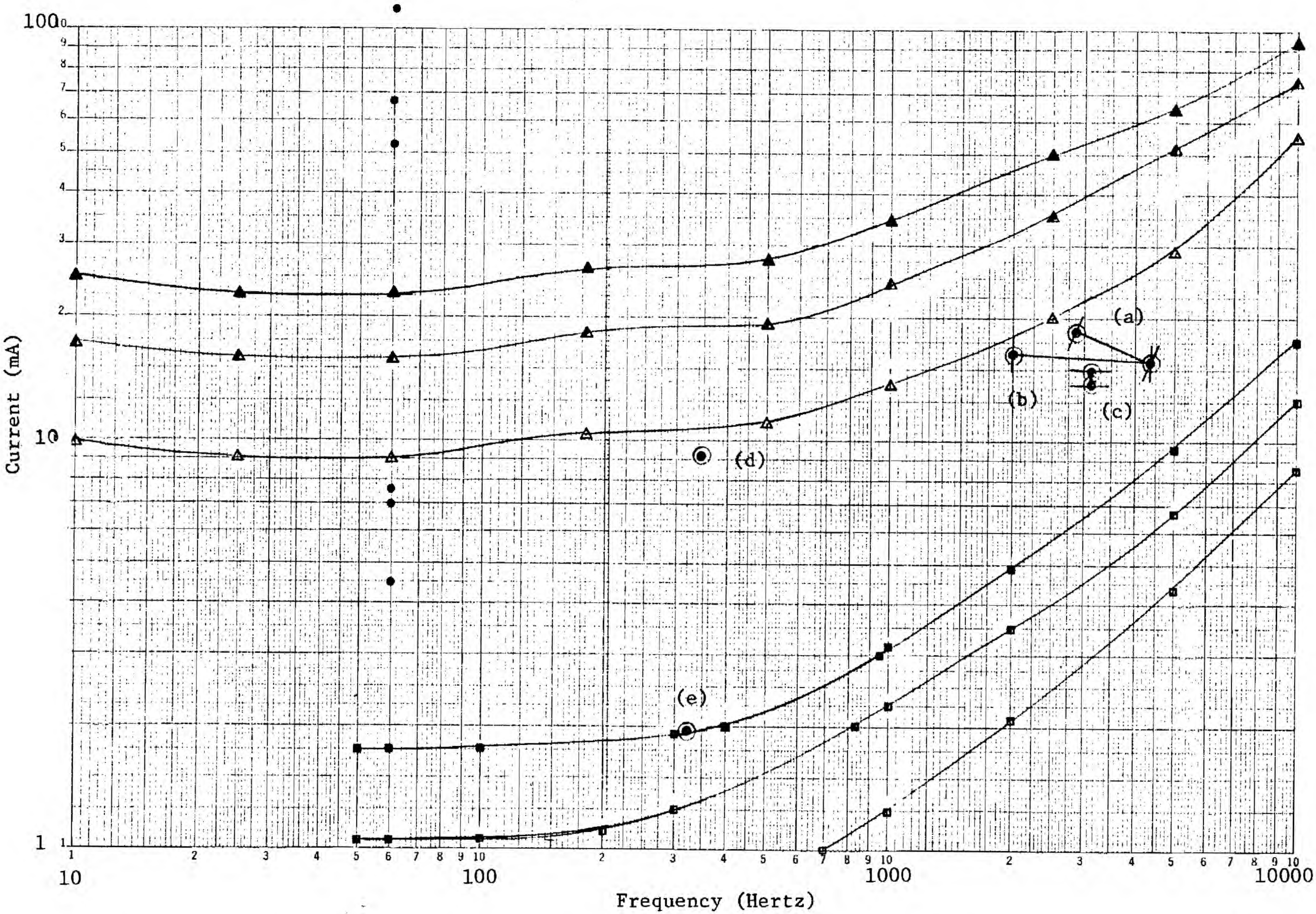

Figure 12. Current Levels Obtained Using the First Sinusoidal Approximation of the Measured Waveforms for (a) 500Ω, (b) 1 KΩ, (c) 10 KΩ, (d) 100 KΩ, and (e) 1MΩ. The Graph is Otherwise Identical to the Plot of Dalziel's Thresholds in Figure 6.

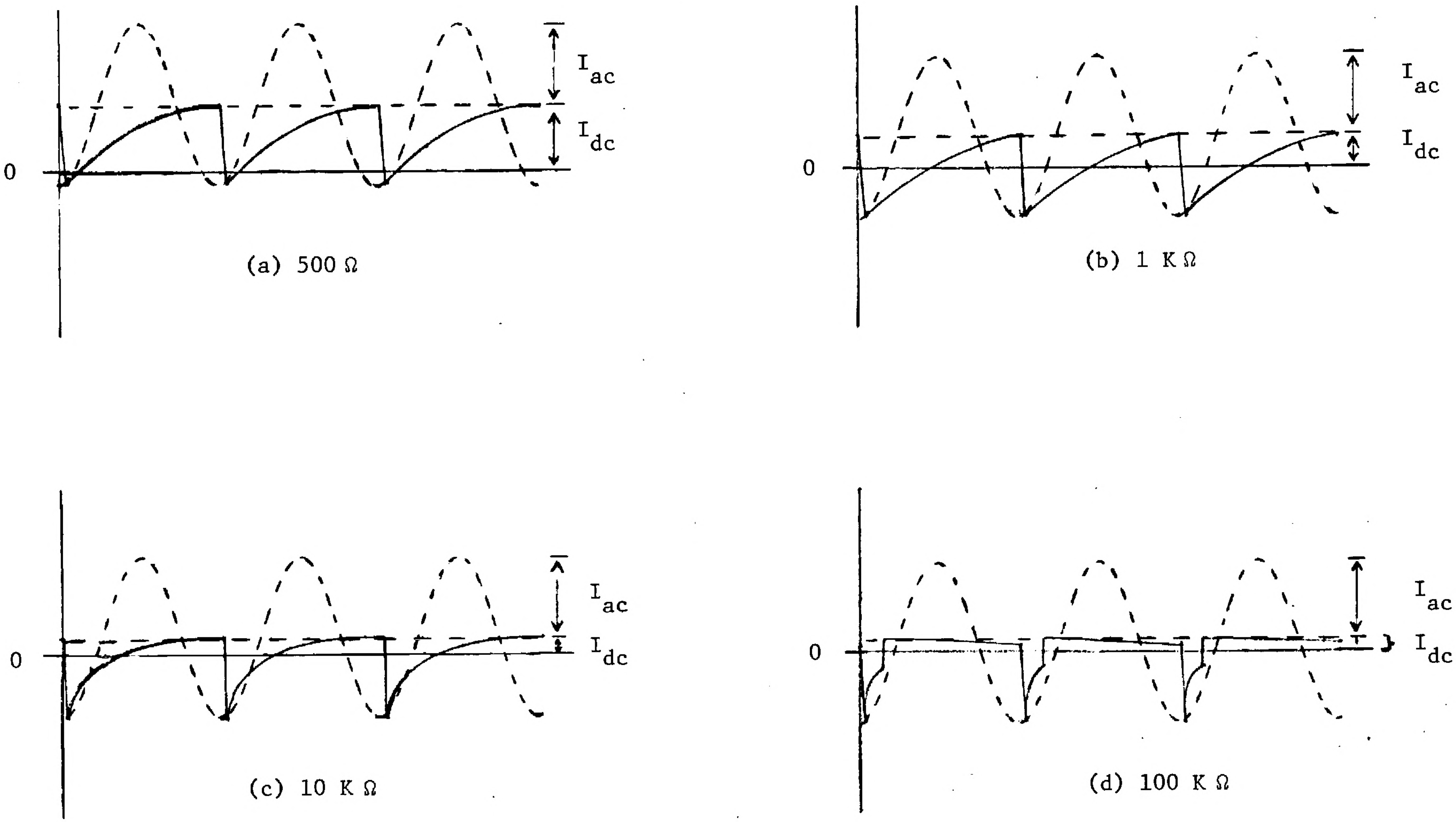

Figure 13. Sketch of the Second Sinusoidal Model Used for the Evaluation of Waveform Safety Superimposed on Reproductions of the Measured Waveforms for Each of the Resistances Tested. The Waveform for the 1 MΩ Resistance is Almost Identical to that for the 100 KΩ Resistance. The Value for I_{dc} is Obtained as Shown, while the Value for I_{ac} is Converted to RMS.

TABLE 5

CALCULATIONS USED TO ESTIMATE THE EQUIVALENT SINUSOIDAL CURRENT
FOR PURPOSES OF COMPARING TO KNOWN SAFETY VALUES*
METHOD #2

Load	I_{dc}	$\lvert I_{ac}\,(peak)\rvert$ $(=\sqrt{2}\ I_{ac})$	$I_{dc} + \sqrt{2}\ I_{ac}$	$2\sqrt{2}\ I_{ac}$	Equivalent I_{ac} (rms)	Frequency
500 Ω	+42 mA	52 mA	94 mA	104 mA	36.8 mA	2857 Hz
	+16 mA	44 mA	60 mA	88 mA	31.1 mA	4348 Hz
1000 Ω	+40 mA	46 mA	86 mA	92 mA	32.5 mA	2000 Hz
	+16 mA	44 mA	60 mA	88 mA	31.1 mA	4348 Hz
10 K Ω	+8 mA	42 mA	50 mA	84 mA	29.7 mA	3125 Hz
	(+6 mA)	(39 mA)	45 mA	(78 mA)	(27.6 mA)	
100 K Ω	+2 ma	26 mA	28 mA	52 mA	18.4 mA	345 Hz
1 M Ω	+0.4 mA	5.4 mA	5.8 mA	10.8 mA	3.8 mA	323 Hz

*Calculations are based on modeling the measured current as a sinusoidal current with the same I_{peak} as the measured currents I_{p-p}.

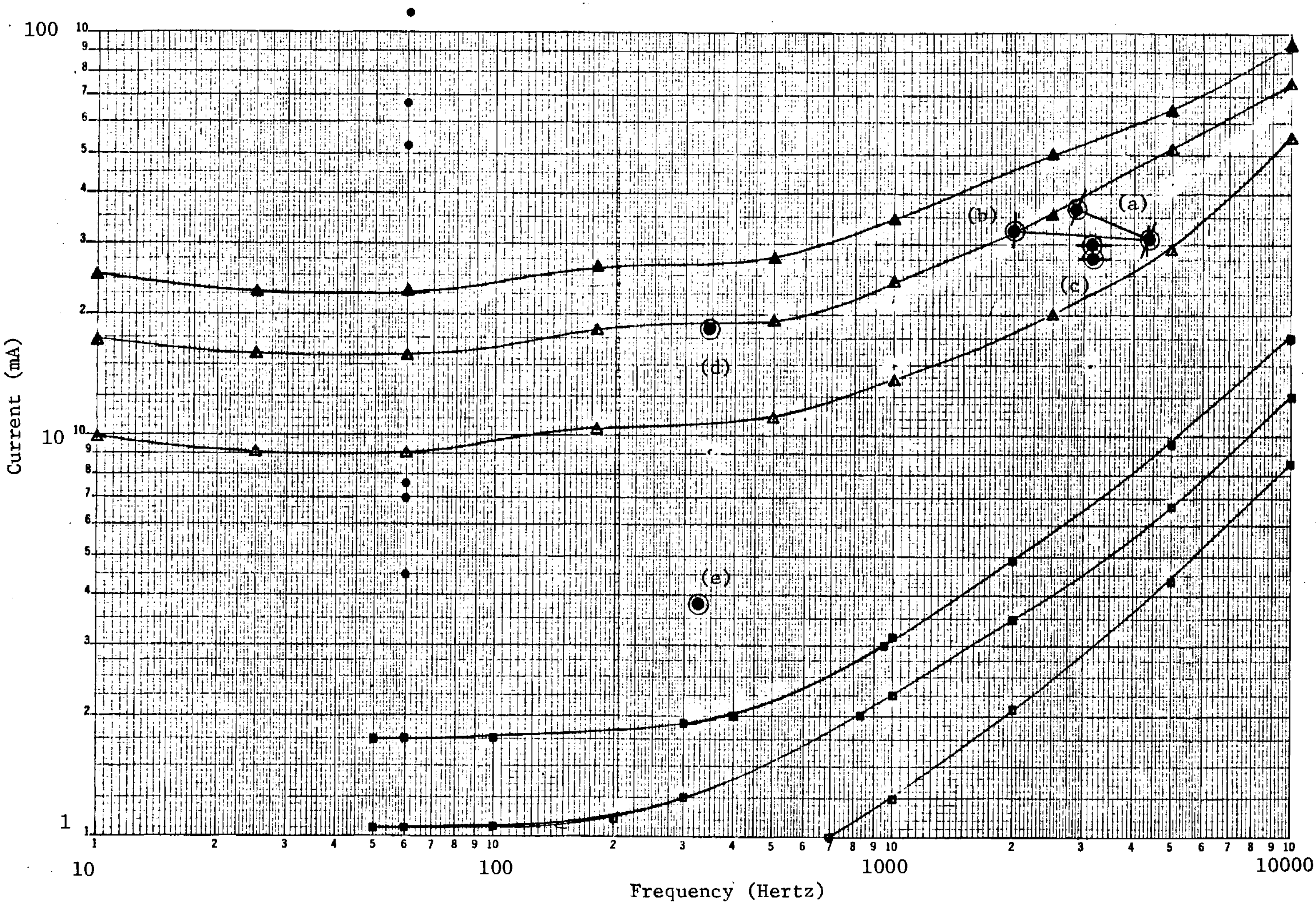

Figure 14. Current Levels Obtained Using the Second Sinusoidal Approximation of the Measured Waveforms for (a) 500 Ω, (b) 1 KΩ, (c) 10 KΩ, (d) 100 KΩ, and (e) 1 MΩ. The Graph is Otherwise Identical to the Plot of Dalziel's Thresholds in Figure 6.

measured waveform in each case. Table 5 lists the calculations involved in interpreting this model and the equivalent rms ac currents obtained. These equivalent currents are then plotted on the Dalziel Threshold curves in Figure 14. All of the plotted points lie on or below the 50th percentile for Let-Go Threshold at their respective frequencies.

Thus, even with the most conservative sinusoidal model of the currents obtained, the currents never exceed the 50 percentile Let-Go Thresholds and thus never even approach the minimum fibrillation level which is above the one-half percentile for Let-Go. Even the maximum I_{p-p} of 42 milliamperes across 500 Ω is much less than the commonly accepted threshold rms current of 100 mA for 60 Hz sinusoidal shocks of 3 seconds or more. It is also much less than the minimum fibrillating current for children of 100 mA (rms) for 60 Hz shocks of 1.0 second duration. It should also be mentioned that these thresholds are even safer when one considers that fibrillating thresholds in the frequency range produced by the Safe Case Design #3 have been shown to be between 5 to 40 times greater than the 60 Hz thresholds mentioned above.

It can therefore be stated with great confidence that the Brink's Safe Case Design #3 is safe for normal healthy adults and possibly even for children with respect to the danger of ventricular fibrillation. In addition, this design is advantageous in that the currents produced are very close to the minimum Let-Go Thresholds over a wide range of resistances, thus ensuring a painful shock. As discussed previously, it is extremely desirable to have a constant current type of device over a wide range of resistances for any type of safe human electrical contact. Safe Case Design #3 provides a fairly consistent peak-to-peak current of from 25-52 mA over the resistances ranging from 500 ohms to 100,000 ohms. From the trend of the data, it is not expected that the peak-to-peak current would ever exceed 60 mA even for resistances lower than 500 ohms. Despite the possibility of a low shock potential for high resistance skin, it must be remembered that skin resistance will always tend to decrease as the duration of electrical contact increases. Thus, even an initially high resistance contact will eventually decrease with time and increase the shock intensity.

Although these currents are close to the Let-Go Thresholds, there is no danger of a victim "freezing" to the Safe Case and not being able to drop it because of the pulsed nature of the current. For each resistance tested the pulse train had an on time of approximately 1 second and an off time of approximately 1 second. Skeletal muscle has a relaxation time typically on the order of 10 msec. Summation of the muscle contractions progressing to tetanus, or "freezing", of the victim to an electrical contact will only occur at stimulation frequencies greater than 10 per second. At these frequencies, the muscles being stimulated do not have enough time to relax completely between contractions, and thus the muscle "freezes". By pulsing the current with current pulse trains with an off time of about 1 second, the hand and arm muscles will have more than ample time to relax completely before the next pulse train, and thus, to let go of the Safe Case. This is the same principle employed in the standards for electric fence controllers which limit the pulse to an on period of 0.2 seconds and an off period of 0.8 seconds [1]. For the purposes of the electric fence, 0.8 seconds is felt to be more than a sufficient period of time for the stimulated muscles to relax and prevent "freezing" to the fence.

The thin mesh fabric surrounding the handle prevents good contact from being made with the case, thus increasing the current density of the contact which in turn increases the skin surface sensitivity to the perception of the current. It is possible that mesh fabric may introduce a capacitive effect which, at these frequencies, may actually serve to lower the total skin impedance and thus increase the intensity of the shock.

Because of the irregular waveforms produced, the energy content of the individual pulses was not as easily calculated as for Designs #1 and #2. In order to simplify the energy calculations, the waveforms were approximated by either two triangles or a triangle and a rectangle below and above the zero voltage baseline. For low resistances that showed a transient change in waveform, the waveform was again described in two parts and separate energy calculations were made for each. The energy content of a triangular waveform is $W = \int (V^2/R)dt = \left(\frac{(V_{max})^2}{R}\right) \cdot \left(\frac{t}{3}\right)$. For a rectangular waveform, the energy content is simply $\left(\frac{(V_{max})^2}{R}\right) \cdot t$. Table 6 lists the calculations made to estimate the energy per impulse (W_p) for each resistance. Again, these are conservative estimates and will tend to overestimate the actual energy present. Using these values for W_p, the total energy in each pulse train (W_T) is estimated by multiplying by the number of pulses present, which in turn is estimated by dividing the total time that the pulse train is on (t_{on}) by the period of the individual pulse (T). Therefore, $W_T = W_P \times (t_{on}/T)$, and these

TABLE 6

CONSERVATIVE CALCULATIONS USED TO ESTIMATE THE ENERGY PER PULSE (W_P) DELIVERED BY SAFE CASE DESIGN #3 TO VARYING RESISTIVE LOADS
(see text for method of approximation)

Load	V_1 (volts)	t_1 (msec)	$W_1 = \frac{(V_1)^2}{R} \cdot \frac{t_1}{3}$ (joules)	V_2 (volts)	t_2 (msec)	Triangle $W_1 = \frac{(V_2)^2}{R} \cdot \frac{t_2}{3}$ (joules)	or =	Rectangle $W_2 = \frac{(V_2)^2}{R} \cdot t_2$ (joules)	$W_P=W_1+W_2$ (joules)
500Ω	-6	0.06	0.07×10^{-4}	+40	0.29	3.09×10^{-4}		---	3.16×10^{-4}
	-15	0.11	0.17×10^{-4}	+13	0.12	1.35×10^{-4}		---	0.305×10^{-4}
1000Ω	-8	0.03	0.006×10^{-4}	+40	0.47	---		7.52×10^{-4}	7.53×10^{-4}
	-30	0.11	0.33×10^{-4}	+20	0.12	0.16×10^{-4}		---	0.49×10^{-4}
10KΩ	-360	0.09	3.89×10^{-4}	+80	0.23	---		1.47×10^{-4}	5.36×10^{-4}
100KΩ	-2500	0.5	104.0×10^{-4}	+200	2.4	---		9.60×10^{-4}	113.6×10^{-4}
1MΩ	-5200	0.3	27.0×10^{-4}	+400	2.7	---		4.32×10^{-4}	31.3×10^{-4}

TABLE 7

CONSERVATIVE CALCULATIONS USED TO ESTIMATE THE ENERGY PER PULSE TRAIN (W_T) DELIVERED BY SAFE CASE DESIGN #3 TO VARYING RESISTIVE LOADS AND THE TEMPERATURE RISE ($^{o}C \cdot cm^3$/PULSE TRAIN) WHICH MIGHT BE EXPECTED IN A VOLUME OF SKIN TISSUE.

Load	W_P (joules)	Time On (t_{on}) (sec)	Pulse Period (T) (msec)	$W_T = W_P \times \frac{t_{on}}{T}$ (joules)		Temperature Rise ($^{o}C \cdot cm^3$/Pulse Train)
500Ω	3.16×10^{-4}	0.03	0.35	0.027	0.156	0.0374
	0.305×10^{-4}	0.97	0.23	0.129		
1000Ω	7.53×10^{-4}	0.03	0.50	0.045	0.262	0.0629
	0.49×10^{-4}	1.02	0.23	0.217		
10KΩ	5.36×10^{-4}	1.0	0.32	1.675		0.402
100KΩ	113.6×10^{-6}	0.9	2.9	3.526		0.846
1MΩ	31.3×10^{-4}	0.9	3.1	0.909		0.218

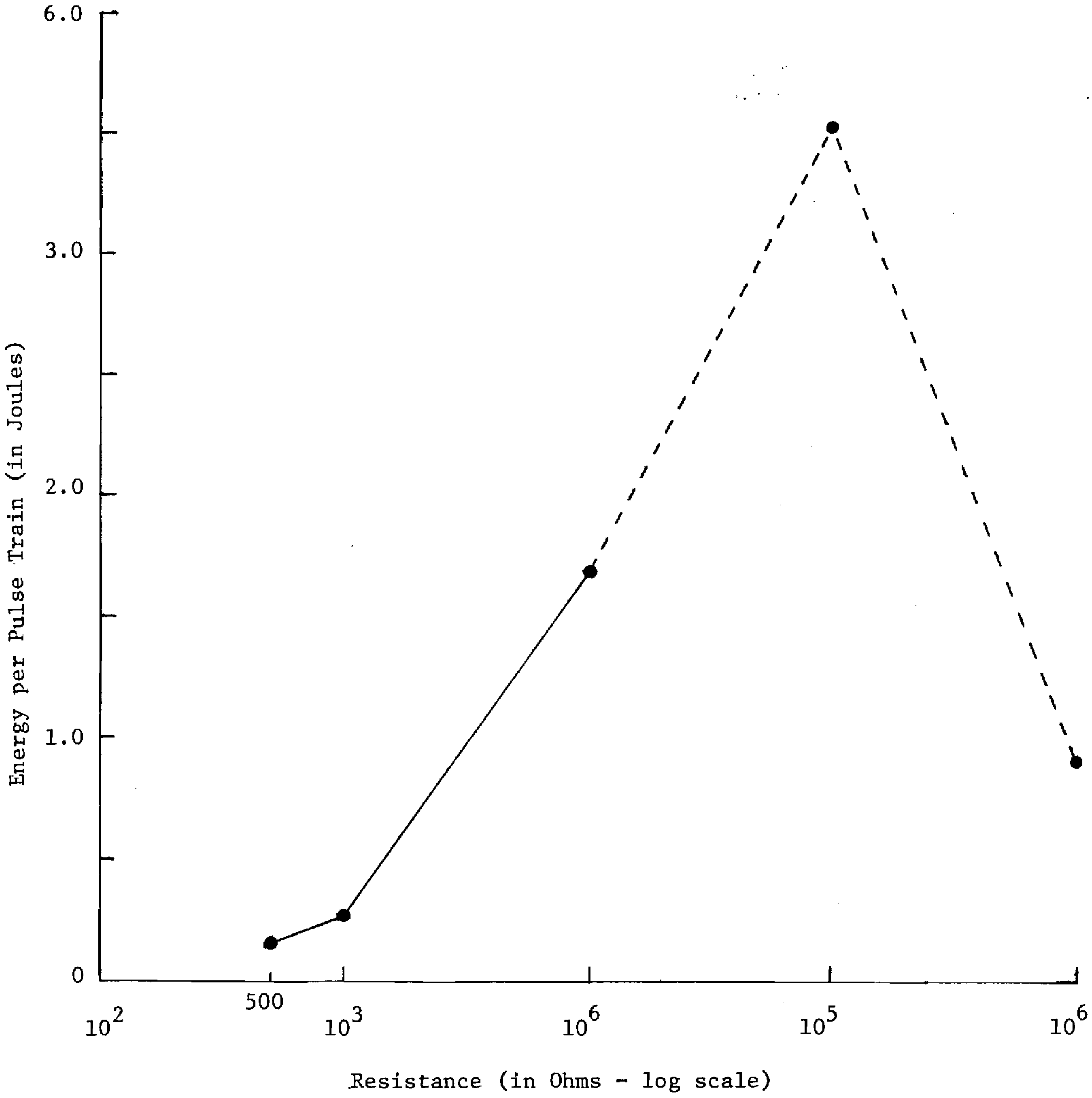

Figure 15. Estimated Energy per Pulse Train (W_T) as a Function of Resistance for Safe Case #3.

values are displayed in Table 7. Based on these estimates, the maximum energy content of any of the pulse trains measured was 3.5 joules and was delivered to the resistance of 100KΩ. Figure 15 is a graphical interpretation of the energy content of the pulse trains (W_T) delivered by Safe Case Design #3 as a function of the tested resistance. As can be seen, the energy delivered to the resistance is maximal at approximately 100KΩ and drops off sharply on either side of this resistance. Unfortunately, there is no way to know if this maximum measured energy represents the true maximal energy output of the Safe Case or not; however, it is doubtful that the maximum energy would ever exceed 5 joules.

The energy output of the pulse train across the 500 ohm load is only 0.156 joules. Thus, this Safe Case design also lies well within the Underwriter's Laboratories Standards for electric fences [1]. However, the pulse duration of approximately 1 second is longer than that recommended for electric fences.

The theoretical temperature rise resulting from the energy discharges from each pulse train is also listed in Table 7 using the same method of modelling and calculation as previously described for Designs #1 and #2. For a skin resistance of 100KΩ, the theoretical temperature rise would be 0.846 $^{o}C\text{-}cm^3$/pulse train. It should be noted that the pulse trains only occur every 2 seconds, therefore it would be more correct in estimating burn hazards with time if these temperature rise values were averaged over 2 seconds. It has already been shown by Henriques and Moritz that repeated subthreshold thermal injuries are cumulative. With a maximum time-averaged temperature rise of 0.423 $^{o}C\text{-}cm^3$/sec, a contact of two 1 cm^3 volumes of skin would have to be maintained for more than 70 seconds to achieve second degree burns. If heating were assumed to be limited to 1 mm depth, contact would have to be maintained for greater than 8 seconds, or over more than 4 pulses. For 2 fingertip contacts of 1 mm x 1 mm dimensions and with an assumed depth of heating of 1 mm, pinhole burns of the surface of the skin would be instantaneous. Thus, although the burn potential is present with Safe Case Design #3, the person stealing the case would have tolerated a great deal of pain and would have plenty of time to decide to drop the case before skin surface burns would become a problem. Even if the maximum energy discharge were as much as 5 joules for some unknown resistance, a person with only two 1

cm^2 surface area contacts would have to maintain that contact for greater than 30 seconds and would have received 15 shocks before second degree burns would appear.

In summary, Safe Case Design #3 is felt to be a safe device for human contact assuming the resistances for human contact are, as stated in the literature, between 500 ohms and 1,000,000 ohms. The currents produced by this device should not be sufficient to cause ventricular fibrillation in the average healthy adult and, presumably, in the average healthy child. Persons coming into contact with the activated device will experience some degree of pain and possibly severe tetanic muscle contractions of the affected extremity. Current off times of 1 second or more are of sufficient duration to allow a person to let-go of the case after even just one shock. If the person insists on tolerating many shocks over a prolonged period of time, there does exist a potential for second degree and even third degree burns.

Finally, it must be recognized that any theoretical thresholds of safety are merely theoretical and not absolute. Such threshold values are designed to be conservative and will give predictions on the side of safety. However, even with ventricular fibrillation thresholds, the best estimate possible is a value that would be safe for 99.5% of the population. That leaves the possibility that 0.5% of the population could go into ventricular fibrillation with a shock below that value. Dalziel has stated:

> "Because of the wide variation in the physical condition of individuals, it is impossible to justify any electric shock as safe for all individuals. The press contains frequent accounts of fatalities ascribed to heart failure caused by overexcitement, intense emotion, fear, or shock. For such susceptible persons, it is possible that contact with any electric circuit which permits currents in excess of the threshold of sensation might result in fatality. This possibility must be recognized, and an occasional death is to be expected from casual contact involving electric currents known to be safe for most normal individuals. Death in such cases must be considered due to shock of the nervous system, and not to the primary effects of electric current." [8]

The purpose of this report is to analyze the possibility of a safety hazard due to the primary effects of electric current. This hazard has been evaluated and Safe Case Design #3 has been found to be reasonably safe for human contact. This statement is not to be interpreted as saying that the Safe Case is 100% safe for everybody it may shock. Electrical contact with the case should be avoided if at all possible. Any person in charge of activating the Case or involved with transport of the Case should have training in CPR (Cardiopulmonary Resuscitation) techniques. Such training is readily available through the American Red Cross, the American Heart Association, and many local civic organizations. In addition, any vehicle involved with the transport of this Case should have easy radio access to ambulance services and emergency facilities. Only under these conditions can the Safe Case by considered as safe as humanly possible.

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